Algorithm Theoretical Basis Document (ATBD) for the Conical-Scanning Microwave Imager/Sounder (CMIS) Environmental Data Records (EDRs)

Volume 12: Ice EDRs

Covering: Sea Ice Age and Sea Ice Edge Motion EDR
Fresh Water Ice EDR

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REVISION HISTORY

Version	Release Date	POC	Comments
1.0	6 Nov., 2000	Galantowicz	Initial partial draft release.
1.1	22 Nov., 2000	Galantowicz	Corrected errors in performance sensitivity to land fraction; editing corrections including measurement uncertainty units in performance tables
1.2	6 Feb., 2001 (PDR)	Galantowicz	-Corrected retrieval errors for points outside PR-GR triangle -Increased simulated emissivity variability to better match estimates in literature -MY ice simulated variability is set lower than literature such that overall ice concentration uncertainty is consistent with heritage methods -Revised performance -Replaced FY/MY prob. correct typing stratification charts to better show dependence on ice concentration and type

RELATED CMIS DOCUMENTATION

Government Documents

Title	Version	Authorship	Date
CMIS SRD for NPOESS Spacecraft and Sensors	3.0	Associate Directorate for Acquisition NPOESS IPO	2 March 2001

Boeing Satellite Systems Documents

<table>
<tr><th colspan="2">Title</th><th>Covering</th></tr>
<tr><td colspan="2">ATBD for the CMIS TDR/SDR Algorithms</td><td></td></tr>
<tr><td rowspan="8">ATBD for the CMIS EDRs</td><td rowspan="2">Volume 1: Overview</td><td>Part 1: Integration</td></tr>
<tr><td>Part 2: Spatial Data Processing
• Footprint Matching and Interpolation
• Gridding
• Imagery EDR</td></tr>
<tr><td>Volume 2: Core Physical Inversion Module</td><td></td></tr>
<tr><td>Volume 3: Water Vapor EDRs</td><td>Atmospheric Vertical Moisture Profile EDR
Precipitable Water EDR</td></tr>
<tr><td>Volume 4: Atmospheric Vertical Temperature Profile EDR</td><td></td></tr>
<tr><td>Volume 5: Precipitation Type and Rate EDR</td><td></td></tr>
<tr><td>Volume 6: Pressure Profile EDR</td><td></td></tr>
<tr><td>Volume 7: Cloud EDRs</td><td>Part 1: Cloud Ice Water Path EDR</td></tr>
</table>

Title		Covering
		Part 2: Cloud Liquid Water EDR
		Part 3: Cloud Base Height EDR
	Volume 8: Total Water Content EDR	
	Volume 9: Soil Moisture EDR	
	Volume 10: Snow Cover/Depth EDR	
	Volume 11: Vegetation/Surface Type EDR	
	Volume 12: Ice EDRs	Sea Ice Age and Sea Ice Edge Motion EDR Fresh Water Ice EDR
	Volume 13: Surface Temperature EDRs	Land Surface Temperature EDR Ice Surface Temperature EDR
	Volume 14: Ocean EDR Algorithm Suite	Sea Surface Temperature EDR Sea Surface Wind Speed/Direction EDR Surface Wind Stress EDR
	Volume 15: Test and Validation	All EDRs

Bold = this document

TABLE OF CONTENTS FOR VOLUME 12

LIST OF TABLES

LIST OF FIGURES

1. Abstract

The CMIS Sea Ice Age and Sea Ice Edge Motion EDR and Fresh Water Ice EDR consist of a suite of related measurements that will be retrieved using a single ice algorithm package. The EDRs' required measurements include fresh water ice concentration, fresh water ice edge boundary, sea ice type by age, sea ice concentration, sea ice edge location, and sea ice edge motion. In nominal algorithm operations, the primary algorithm package inputs are atmospheric Core Module-retrieved emissivities. Emissivity inputs provide data that are sensitive to surface composition and corrected for interfering temperature and atmospheric effects using the full complement of CMIS channels. Alternative algorithm modes also allow for direct input of top-of-atmosphere brightness temperatures. In this ATBD we describe the physical basis and mathematical and logical structure of each part of the algorithm package, their inputs, their implementation and data flow including integration within overall CMIS processing, and expected retrieval performance based on simulations and SSM/I real-data tests. Performance is expected to meet or exceed EDR requirements. Algorithm calibration procedures, testing, and operational considerations are discussed.

2. Introduction

2.1. Purpose

The purpose of this document is to provided all the information necessary to understand, operate, further develop, and use the products from the CMIS ice retrieval algorithm package. The CMIS SRD (NPOESS IPO, 2000) specifies the EDRs' required (threshold level) operational and performance characteristics including definitions, spatial resolution, and measurement range, uncertainty, and probability of correct typing (for ice age-type). The integrated ice algorithm package (Core Module plus ice algorithm package) meets these specific requirements by deriving its products solely from CMIS brightness temperature observations. Furthermore, the algorithm reports additional products that extend the retrieval capabilities and aid quality control.

Section 3 summarizes the EDR requirements either specified in the SRD or derived from it. It contains a historical background and physical basis for the proposed algorithm, and it describes the instrument characteristics and data from all sources necessary to meet NPOESS requirements.

Section 4 describes the physical parameterizations relevant to the ice retrieval algorithm. We also provide algorithm processing flow diagrams including dependencies within the overall processing flow and list input and output fields and ancillary databases.

Section 5 presents both simulations and real-data test results and provides measurement uncertainty, probability of correct typing, and other performance estimates based on the tests. These estimates are used to demonstrate that the algorithm products will satisfy retrieval performance requirements. We describe the environmental conditions under which we expect the retrievals to meet requirements, not to meet requirements, or to degrade substantially. We also summarize special constraints, limitations, or assumptions made in algorithm parameterization or testing that may limit the algorithm's applicable domain or necessitate post-launch adjustments based on specific systematic contributions in order to meet performance estimates.

Section 6 discusses algorithm calibration points and outlines the steps necessary to transition algorithm operation from simulated-data to a CMIS-data inputs. We outline considerations for pre- and post-launch calibration and validation efforts, including needed measurement capabilities and hardware, field measurements, and existing sources of truth data.

Section 7 describes practical considerations including numerical computation considerations, algorithm quality control and diagnostics, exception and error handling, and archival requirements.

2.2. Document Scope

The *ATBD for the CMIS Ice EDRs* covers algorithm operations beginning with the ingestion of earth-gridded Core Module products (surface effective broad-band atmospheric window-channel emissivities) and/or top-of-atmosphere brightness temperatures and concluding with the reporting of the various components of the Sea Ice Age and Sea Ice Edge Motion and Fresh Water Ice EDRs and other related algorithm products on the same earth-grid. Preceding sensor data processing steps are covered in the *ATBD for SDR Processing* and *ATBD for the Core Physical Inversion Module* (AER, 2000). This ATBD provides outlines for continued algorithm development and advancement and for pre- and post-launch calibration/validation efforts. These outlines are intended to be reviewed and revised prior to launch as new data sources and research become available.

3. Overview and Background Information

3.1. Objectives of the ice EDR retrievals

The ice EDRs are specific measurement that CMIS must perform to complete the mission objectives stated in the SRD: "The mission of CMIS is to provide an enduring capability for providing measurements on a global basis of various atmospheric, land, and sea parameters of the Earth using microwave remote sensing techniques. The CMIS instrument will collect relevant information from a spaceborne platform, and utilize scientific algorithms to process that information on the ground into designated [EDRs]." (SRD, section 3.1.7)

3.1.1. Objectives of the Sea Ice Age and Sea Ice Edge Motion EDR retrievals

The SRD requires that the CMIS ice algorithm package retrieve four products over the global oceans: Sea ice age as the typing of areas of sea ice by age (first year and multi-year types at a minimum), sea ice concentration as the fraction of a given area of sea water covered by ice, sea ice edge location as the boundary between ice-covered sea water and open sea water, and sea ice motion as the displacement rate of a sea ice edge. The algorithm will provide an instantaneous measurement of each of these parameters in clear and cloudy (non-precipitating) conditions with the first two as averages over a 20 km cell and the last two as map contour and vector (speed and direction) data, respectively. Sea ice age and concentration products will be valuable for monitoring regional climate factors and local conditions whether clear, cloudy, day or night. Sea ice edge and sea ice edge motion—both derived from the concentration retrievals—will provide additional value for navigation and oceanography applications and continuity with manual-analysis products.

The algorithm will also provide quality control products and an ice mask product to be used by other EDR algorithms. To provide data to other algorithms, the ice algorithm will be executed both early in the processing flow using brightness temperatures as well as later in the flow using Core Module-retrieved emissivities for final EDR retrievals.

The CMIS sea ice products will complement similar EDRs required for VIIRS—sea ice age and sea ice edge motion. Whereas CMIS can make instantaneous measurements in all non-precipitating conditions, the higher-resolution VIIRS retrieval will require clear skies and may have reduced skill with low solar zenith angle or nighttime conditions.

3.1.2. Objectives of the Fresh Water Ice EDR retrievals

The SRD requires that CMIS retrieve ice concentration and the ice edge boundary on fresh water bodies with characteristics similar to the corresponding sea ice products. The algorithm will provide an instantaneous measurement of these parameters in clear and cloudy (non-precipitating) conditions with ice concentration as an average over a 20 km cell and ice edge boundary as map location data. Fresh water ice concentration will be valuable for monitoring climate factors and local conditions whether clear, cloudy, day or night. Ice edge boundary—derived from concentration retrievals—will provide additional value for navigation and limnology applications and continuity with manual-analysis products.

The algorithm will also provide quality control products and an ice mask product to be used by other EDR algorithms. To provide data to other algorithms, the ice algorithm will be executed both early in the processing flow using brightness temperatures as well as later in the flow using Core Module-retrieved emissivities for final EDR retrievals.

The CMIS fresh water ice products will complement similar EDRs required for VIIRS. Whereas CMIS can make instantaneous measurements in all non-precipitating conditions, the higher-resolution VIIRS retrieval will require clear skies and may have reduced skill with low solar zenith angle or nighttime conditions.

3.2. Summary of EDR requirements

3.2.1. SRD Requirements

The text and tables below are the portions of CMIS SRD section 3.2.1.1.1.1 that apply directly to the ice algorithm package. Shading indicates attributes not addressed at all in this document.

> **Sea Ice Age and Sea Ice Edge Motion** **TRD App D Section 40.7.8**
>
> The requirements below apply under both clear and cloudy conditions. Sea ice age is defined as the time that has passed since the formation of the surface layer of an ice covered region of the ocean. The content of the sea ice age EDR is the typing of areas of sea ice by age. Sea ice motion is defined as the displacement of a sea ice edge. Definitions of the Ice Age Classes are included below. [See Appendix 1: Definitions of the Ice Age Classes.] Ice concentration is defined as the fraction of a given area of sea or water covered by ice. An ice edge is defined as the boundary between ice-covered sea water (ice concentration > 0.1) and sea water not covered by ice (ice concentration ≤ 0.1).

Table 3-1: SRD Requirements for the Sea Ice Age and Sea Ice Edge Motion EDR

Para. No.		Thresholds	Objectives
C40.7.8-1	a. Horizontal Cell Size	20 km	0.1 km
C40.7.8-2	b. Horizontal Reporting Interval	(TBD)	(TBD)
C40.7.8-3	c. Horizontal Coverage	Oceans	Oceans
	d. Measurement Range		
C40.7.8-4	1. Ice Age Classes	First Year, Multi-year	New, Young, First Year, and Old
C40.7.8-5	2. Ice Motion	0-50 km/day	0 – 50 km/day
C40.7.8-6	e. Probability of Correct Typing (Ice Age)	70 %	90 %
C40.7.8-7	f. Measurement Uncertainty (Ice motion)	1 km/day	0.1 km/day
C40.7.8-8	g. Mapping Uncertainty	3 km	1 km
C40.7.8-9	h. Swath Width	1700 km	3000 km (TBR)
C40.7.8-10	i. Measurement Uncertainty (Ice Edge Location)	(TBD)	(TBD)
C40.7.8-11	j. Measurement Range (Concentration)	0.1 – 1 (0.1 increments)	0 – 1 (0.1 increments)
C40.7.8-12	K. Measurement Uncertainty (Concentration)	0.1 or 20%	10%

Fresh Water Ice **TRD App D Section 40.7.2**

Fresh water ice concentration is defined as the fraction of a given area of fresh water that is covered by ice, quantized to the nearest one tenth. Ice edge boundary is the contour separating fresh water from fresh water ice. The error in ice edge boundary location is defined as the distance between a measured boundary point and the nearest point on the true ice edge boundary. The measurement uncertainty requirement on ice edge boundary limits this error.

Table 3-2: SRD Requirements for the Fresh Water Ice EDR

Para. No.		Thresholds	Objectives
	a. Horizontal Cell Size		
C40.7.2-1	1. Nadir	20 km (TBR)	(TBD)
C40.7.2-2	2. Worst case	20 km (TBR)	(TBD) 0.65 km
C40.7.2-3	b. Horizontal Reporting Interval	(TBD)	(TBD)
C40.7.2-4	c. Horizontal Coverage	Global: Fresh Water	Global: Fresh Water
C40.7.2-5	d. Measurement Range	1/10 to 10/10 concentration	0/10 to 10/10 concentration
C40.7.2-6	e. Measurement Uncertainty		
C40.7.2-7	1. Ice Edge Boundary	10 km	5 km
C40.7.2-8	2. Ice Concentration	20 % or 1/10	10 %
C40.7.2-9	f. Mapping Uncertainty	3 km	1 km
C40.7.2-10	g. Swath Width	1700 km (TBR)	(TBD)

In addition to these requirements, the SRD specifies:

1. "Science algorithms shall process CMIS data, and other data as required, to provide the [EDRs] assigned to CMIS." (SRD, paragraph SRDC3.1.4.2-1)
2. "Specified EDR performance shall be obtained for any of the orbits described in paragraph 3.1.6.3 …" (SRDC3.1.6.3-2)
3. "As a minimum, the EDR requirements shall be satisfied at the threshold level." (SRDC3.2.1.1.1-3)

4. "… the contractor shall identify the requirements which are not fully satisfied, and specify the conditions when they will not be satisfied." (SRCD3.2.1.1.1-4)
5. "… CMIS shall satisfy the EDR Thresholds associated with cloudy conditions under all measurement conditions …" (SRD SRDC3.2.1.1.1.1-1)
6. "[The definition of] Probability of Correct Typing [is] probability that a horizontal cell reported as being of type x is in fact of type x, where x is any allowed type." (SRD Appendix A)

Also note that the CMIS system consists "of all ground and spaceborne hardware and software necessary to perform calibrated, microwave radiometric measurements from space and the software and science algorithms necessary to process … these measurement into a format consistent with the requirements of the assigned [EDRs]." (SRD, section 3.1.1)

3.2.2. Requirements interpretations

We infer the following statements as either direct consequences or clarifications of the SRD requirements stated above and take them as requirements to be satisfied by the ice algorithm package or to be addressed through algorithm performance evaluation:

1. For requirements in which both a percentage value and an absolute value are supplied in the tables above, the requirement is the greater of the values. For example, for 2/10 fresh water ice concentration, the measurement uncertainty is 1/10 not 0.04 (20% of 2/10).
2. The definition of ice edge given for the Sea Ice EDR applies to the Fresh Water Ice EDR. That is, for fresh water ice: "An ice edge is defined as the boundary between ice-covered fresh water (ice concentration > 0.1) and fresh water not covered by ice (ice concentration ≤ 0.1)."
3. The definition of error in ice edge boundary location given for the Fresh Water Ice EDR applies to the Sea Ice EDR. That is, for sea ice: "The error in ice edge boundary location is defined as the distance between a measured boundary point and the nearest point on the true ice edge boundary. The measurement uncertainty requirement on ice edge boundary limits this error."
4. "Horizontal coverage[:] Global: Fresh Water" specifies that the fresh water ice products will be retrieved for a finite list of permanent water bodies (that is, not including temporary inundation events) to be specified by the user. Table 3-3 provides a list of candidate lakes that are greater than 3500 km^2 in size and subjected to below freezing weather at least 80 days/year (source: International Lake Environment Committee Foundation, Kusatsu, Shiga, Japan).

Table 3-3: Initial Candidate list of Fresh Water Lakes

Location	Lake Name	Surface Area (km^2)
North America	Superior	82,400
	Huron	59,600
	Michigan	58,000
	Great Bear Lake	31,100
	Great Slave Lake	28,600
	Erie	25,800
	Winnipeg	23,800
	Ontario	19,000
	Athabasca	7,900
	Reindeer	5,700
	Winnipegosis	5,200
	Netilling	5,100
	Manitoba	4,600
	Nipigon	4,500
Eurasia	Baikal	31,500
	Balkhash	18,200
	Ladoga	18,100
	Onego	9,900
	Vanern	5,600
	Peipus	3,600

3.2.3. Derived requirements on the ice algorithm package

Other algorithms have imposed additional requirements on the ice algorithm package for pre-classification of the surface based on top-of-atmosphere brightness temperatures.

- The Core Module requires that a binary ice-or-ocean flag retrieved from brightness temperatures on composite footprint retrieval cells. At least 99% of cells with any ice must be flagged. Percentage of all-ocean cells incorrectly flagged as ice may be as high as 5%. Detection of fresh water ice is not required.
- The sea EDR algorithm suite requirements are (TBD).

3.3. Historical and background perspective of proposed algorithm

Operational and/or retrospective retrievals of sea ice properties from CMIS-heritage instruments (e.g., ESMR, SMMR, SSM/I) date back to 1973 (Gloersen et al., 1993). The typical product from this record is the simultaneous retrieval of first-year ice, multi-year ice, and open water concentrations in the field-of-view. In this approach, the total ice concentration is a secondary product—the sum of first-year and multi-year concentrations. Since first-year and multi-year ice concentrations were simultaneously retrieved, ice type per retrieval cell was not explicitly provided. (It can be inferred from the concentrations as the dominant type per cell.) The heritage retrievals were limited by the horizontal spatial resolutions (HSR) of the 19 GHz channels: 55 km for SMMR and 69 km for SSM/I.

Ice edge location and ice edge motion products are secondary products readily derived from retrieved concentrations by image analysis. Algorithms for sea ice motion within the ice-pack exist and have been extensively applied to SSM/I data (for example, Emery et al., 1997).

Although operational systems also retrieved fresh water ice concentration for northern water bodies, no special adjustments of the algorithm for sea ice-fresh water ice spectral differences were made. There are no published passive microwave fresh water ice concentration retrieval algorithms.

The CMIS EDR requirements above build on the heritage products by imposing a set of additional attributes and performance criteria. Key among these is the 20 km horizontal cell size requirement which represents a significant improvement upon the current (SSM/I) and past (SMMR) operational products. The following items summarize some of the defining attributes of the CMIS system, requirements, and retrieval approach:

1. The CMIS system will perform atmosphere temperature and water vapor sounding using channels that are either completely or partially insensitive to the surface conditions. To produce the ice EDRs, the ice algorithm suite will ingest surface emissivities and effective temperature retrieved by the Core Module atmospheric algorithm (see *ATBD for the Core Physical Inversion Module*, AER 2000). The Core Module can retrieve emissivity accurately over a wide range of surface and atmospheric conditions and functions as a "weather filter" for ice EDR retrievals.
2. The required sea ice product set includes ice type (that is, one type per cell) and total ice concentration but not separate concentrations reported for each type. These concentrations are produced by the algorithm and will be reported for continuity with past operational products.
3. The fresh water ice concentration and ice edge boundary are new products without a significant passive microwave operational heritage.
4. The sea ice edge location and ice edge motion are new products without a passive microwave operational heritage.

3.4. Physics of Problem

All the ice EDR retrievals are based on the strong contrasts in spectral emissivity and brightness temperature that exist among various types of ice and open water. This section explains the physical conditions required to retrieve ice type concentrations from both brightness temperatures and Core Module-retrieved emissivities.

Ice concentration sensitivity

As a simple example, when N components with different emissivities fill the sensor field of view and each covers portion f_i, the specular reflectivity is given by

$$r = \sum_{i=1}^{N} f_i r_i \tag{1}$$

and the surface-emitted brightness temperature is

$$T_{Bs} = \sum_{i=1}^{N} f_i T_i e_i \tag{2}$$

where T_i, r_i, and e_i are the effective emitting temperature, reflectivity, and emissivity (1-r_i) of scene component i, respectively. Assuming a plane-parallel atmosphere with optical depth τ and up-welling and down-welling brightness temperatures T_{UP} and T_{DN}, the scene brightness temperature at the sensor is approximately

$$T_B = T_{Bs}e^{-\tau} + T_{UP} + rT_{DN}e^{-\tau}. \tag{3}$$

Consider a two-component scene, $f_2 = 1 - f_1$. Then

$$T_B = T_{UP} + (T_2e_2 + r_2T_{DN})e^{-\tau} + f_1[T_1e_1 - T_2e_2 - T_{DN}(e_1 - e_2)]e^{-\tau}. \tag{4}$$

Here, T_B sensitivity to the concentration f_1 depends on the following conditions: 1) difference between e_1 and e_2, 2) difference between T_1e_1 and T_2e_2, 3) optical depth, 4) T_{DN} (which increases with optical depth), and 5) difference between emitting temperatures and T_{DN}. Higher emissivity contrast insures good f_1 sensitivity provided that counter-acting effects are minimal. Low optical depths in polar regions minimize T_{DN} while increasing f_1 sensitivity from surface emission terms. If $T_1 = T_2$ then the bracketed expression becomes $[(e_1 - e_2)(T - T_{DN})]$. Although higher T_{DN} (which is typically less than 50 K for channels at 19 or 37 GHz) improves conditions for measuring scene emissivity (discussed below), it reduces f_1 sensitivity. When $T_1 \neq T_2$, f_1 sensitivity is unlikely to be enhanced for ice concentration problems. For example, in water/ice scenes, water will have lower 19 GHz emissivity but typically higher temperatures that reduce the effect. And in ice/ice scenes, emissivity is likely to be uncorrelated to temperature.

Figure 3-1 illustrates the differentiation of first-year sea ice (FY), multi-year sea ice (MY), and open water (OW) using a gradient ratio (GR) vs. polarization ratio (PR) scatter plot. (Similar plots for fresh water ice are given in sections 5.2.1 and 5.5.2.) GR and PR are defined as:

$$\mathrm{PR} = \frac{\mathrm{TB19V} - \mathrm{TB19H}}{\mathrm{TB19V} + \mathrm{TB19H}} \qquad \mathrm{GR} = \frac{\mathrm{TB37V} - \mathrm{TB19V}}{\mathrm{TB37V} + \mathrm{TB19V}}. \tag{5}$$

PR and GR form the basis of many sea ice retrieval algorithms including the NASA Team algorithm whose ice triangle overlays the data (Cavalieri et al., 1984, Cavalieri and Comiso, 2000). In PR-GR space, scenes with 100% open water, first-year ice, and multi-year ice cluster in distinct regions at the triangle corners while water-ice and FY-MY mixed scenes are distributed between them. As discussed in section 4.2, the triangle vertices are defined by evaluating PR and GR using brightness temperatures drawn from so-called tie-points where FY, MY, or OW concentrations are 100%. The PR-GR transformation of the brightness temperature space has two key advantages: It maximizes ice-ocean and FY-MY sensitivity using both the lower-frequency polarization difference for dielectric effects (ice-ocean) and the spectral difference for surface scattering effects (FY-MY); and it minimizes variations due to temperature by normalizing the differences. Most of the deviation around the ice triangle is due to environmental noise—atmospheric effects, temperature, and varying emissivities. A radiometer with NEDT of 0.5 K measures PR and GR to within 0.0015 (ice) or 0.003 (water), so sensitivity without environmental noise is about 2% along the FY-MY line in GR space and about 1% along the FY-OW line. In comparison, ice concentration retrieval uncertainties of 5-10% have been reported for retrieval algorithms without atmospheric corrections (Cavalieri et al., 1984; Cavalieri and Comiso, 2000). Algorithm retrieval performance predictions including environmental noise are discussed in section 5.

Figure 3-1: PR-GR scatter plot of SSM/I TBs with NASA Team algorithm ice triangle overlay. Green: Points set to 0% ice in the algorithm using threshold tests.

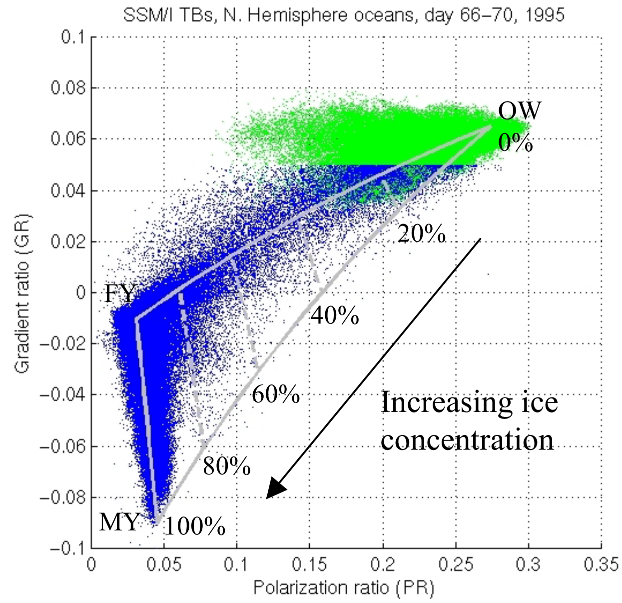
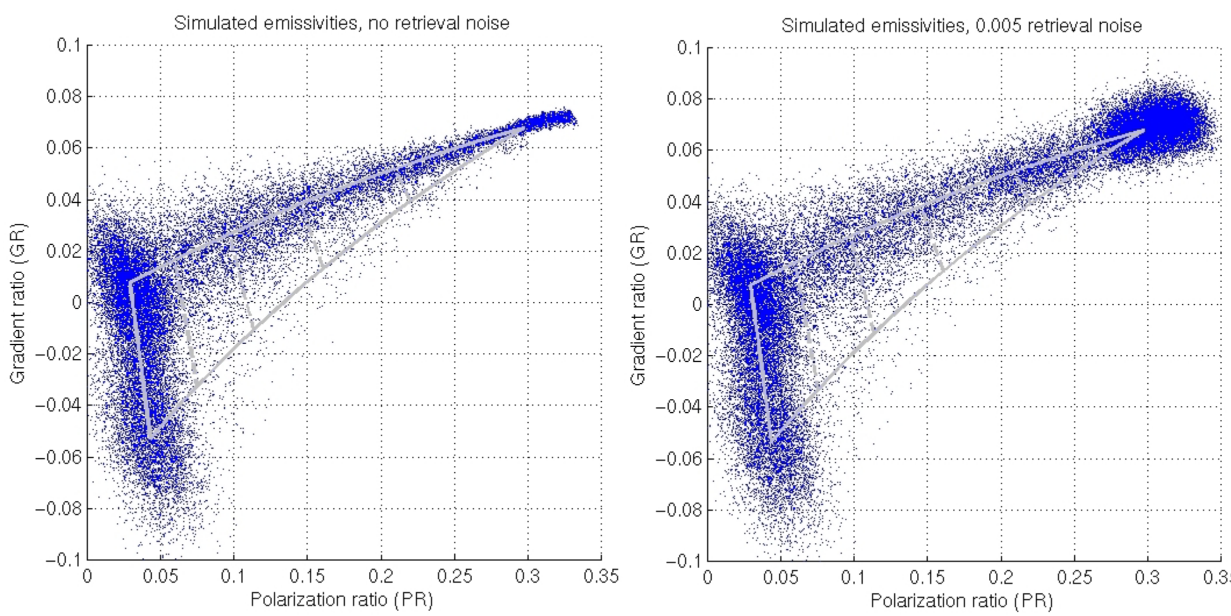


Figure 3-2 is similar to Figure 3-1 but is based on PR and GR calculated from simulated emissivity retrievals with 0.0 and 0.005 retrieval noise. (TB is replace with e in equation 5.) Simulated "true" scene emissivities are generated using (1) to combine random realizations of e_i for each scene component with scene fraction f_i. FY and MY ice emissivity is given by mean values drawn from experimental data (Eppler et al., 1992) plus random environmental noise (see Table 5-9); ocean emissivity is given by a physical model (Wilheit, 19XX) with randomly varying wind speed (0-15 m/s), temperature, and salinity inputs. (Section 5.2.1 provides more information on the simulation environment.)

Figure 3-2: PR-GR scatter plot of simulated emissivities with NASA Team algorithm ice triangle overlay. Left: 0.0 simulated emissivity retrieval error. Right: 0.005 error.



We used mean FY, MY, and OW emissivities to define a emissivity-based ice triangle. The emissivity and brightness temperature ice triangle vertices differ due primarily to the effects of the intervening atmosphere. Similarly, the atmospheric effects causing the distribution of OW points in Figure 3-1 are not present in the emissivity plots. Deviation around the ice triangle is due to a combination of environmental emissivity variability (primarily for ice) and emissivity measurement noise (primarily for water), with water emissivity variability dominated by wind conditions. (Because water emissivity is provided by a physical model, there are strong inter-channel correlations that limit variability in the PR-GR plane. Added 0.005 channel-independent emissivity measurement noise reduces those correlations resulting in the increased spread in Figure 3-1.) A measurement system with 0.005 emissivity error measures PR and GR to within 0.004 (ice) or 0.008 (water), so sensitivity is about 7% along the FY-MY line in GR space and about 3% along the FY-OW line. With 0.0075 emissivity error, PR and GR are measured to within 0.006 (ice) or 0.012 (water), and sensitivity is about 10% along the FY-MY line in GR space and about 5% along the FY-OW line. Emissivity-space sensitivities are worse than TB-space (cited above) but include the cost of removing atmospheric and surface temperature environmental noise from the data. Even when residual environmental noise due to emissivity variability is included, emissivity-based retrieval uncertainty is potentially better than TB-based uncertainty provided that emissivity is accurately resolved.

Emissivity measurement

Emissivity measurement is discussed in detail in the *ATBD for the Core Physical Inversion Module* (AER, 2000). For the ice concentration problem, two key factors affecting emissivity retrieval uncertainty are atmospheric characteristics over ice scenes and scene temperature heterogeneity. Referring back to equation (3), if the T_i are equivalent, then (3) simplifies to

$$T_B = Te^{-\tau} + T_{UP} - r(T - T_{DN})e^{-\tau} . \tag{6}$$

In this case, T_B sensitivity to emissivity is proportional to T-T_{DN} and atmospheric transmittance and increases as transmittance approaches 1 and T_{DN} approaches 0. But although emissivity sensitivity is high through cold, dry atmospheres typical in polar or winter scenes, conditions there are not necessarily more favorable for emissivity retrieval. For instance, the Core Module's full-spectrum retrieval approach exploits spectral emissivity covariance and the differing sensitivity of different frequencies to reflected atmospheric radiation to separate surface emission from atmospheric signals. Consequently, the CMIS channel set must include sounding frequencies with varying degrees of surface sensitivity in thin atmospheres.

In more typical scenes where T_i are no equivalent, it is impossible to completely separate emitting temperature and emissivity terms. Expanding T_{Bs} in equation (3), we have

$$T_B = \left[\overline{T}e + \sum \Delta T_i f_i e_i\right]e^{-\tau} + T_{UP} + rT_{DN}e^{-\tau} . \tag{7}$$

Where $\overline{T}$ is the *f*-weighted average scene temperature and ΔT_i is the deviation of component *i* around $\overline{T}$. The Core Module physical model describes one emissivity ($e_m = 1 - r_m$) and one temperature T_m which have the following relationship to the surface emission terms in (7):

$$T_m e_m = \overline{T}e + \sum \Delta T_i f_i e_i . \tag{8}$$

When emissivity sensitivity is dominated by atmospheric reflection, then e_m will be retrieved as 1 - r (neglecting measurement noise) and the retrieved value for T_m will approximate $\overline{T}$ as:

$$T_m = \overline{T} + \frac{\sum \Delta T_i f_i e_i}{e}. \qquad (9)$$

Given a split FY-OW scene with T = 263-273 K, the $\overline{T}$ error represented by (9) is between -0.2 K (37V) and -2 K (19H). Nevertheless, this is the desirable scenario for ice concentration retrieval because e is retrieved most accurately. Conversely, if the surface is sensed through the emission term only—that is, with no atmosphere—and $T_m = \overline{T}$ by algorithm definition (achieved through tuning, for example), then e_m is related to the true f-weighted emissivity as:

$$e_m = e + \frac{\sum \Delta T_i f_i e_i}{\overline{T}}. \qquad (10)$$

Given the same FY-OW scene, the e error in (10) is between -0.0006 (37V) and -0.004 (19H).

3.5. Instrument characteristics and derived requirements

CMIS is a conically-scanning microwave radiometer with window channels—frequencies chosen to avoid atmospheric absorption lines—around 6, 10, 19, 37, and 88 GHz and atmospheric sounding channel families around 23, 50-60, 60, 166, and 183 GHz. The instrument rotates continuously at 31.6 rpm on an axis perpendicular to the ground taking observations along nearly semi-circular arcs centered on the satellite ground track. Successive arcs scanned by a single sensor channel are separated by about 12.5 km along-track (depending on satellite altitude.) Calibration data is collected from a source (hot) and deep-space reflector (cold) viewed during the non-earth-viewing portion of the rotation cycle. Each observation (or sample) requires a finite sensor integration time which also transforms the sensor instantaneous field of view (IFOV)—the projection, or footprint, of the antenna gain pattern on the earth—into an observation effective field of view (EFOV). The start of each sample is separated by the sample time which is slightly longer than the integration time. The sample time is t_s = 1.2659 ms for all channels with the exception of 10 GHz (exactly 2t_s) and 6.8 GHz (4t_s). All samples fall on one of three main-reflector scan-arcs or a single secondary-reflector scan arc (166 and 183 GHz channels only).

Sensor sample processing (described in the *ATBD for Common EDR Processing Task*, AER, 2000) creates composite measurements which are the spatial weighted superposition of a contiguous group of sensor samples. Although not exact, the process is designed to match observations from different channels to a single reference footprint: The composite fields-of-view (CFOVs) from different channels are more closely matched and collocated than the corresponding EFOVs. In addition, because sensor noise (as measured in NEDT) is both random and independent between samples, the effective NEDT of composite footprints may be reduced (amplified) if the square-root of the sum of squared sample weights is less than (greater than) one. The ice algorithm package uses data processed to match 20x20 km reference footprints.

Table 3-4 lists specific characteristics relevant to the ice EDRs for each sensor channel. (Sounding channel families around 50-60 and 183 GHz are listed as groups. Other channels that are neither H or V pol. are not listed.) Channels that are applied to ice EDR retrieval are marked either as required to meet or approach threshold requirements (X) or used to meet or approach objectives (O). Many channel combinations that exclude some of those marked with an X will also meet threshold requirements. The minimum channel set—one that meets all threshold requirements with the fewest channels—includes 18V, 18H, 22V, and 36V channels. Additional channels above 18 GHz can enhance performance of the Core Module's emissivity retrieval product. See section 5.3 for more detailed estimates of performance degradation with limited channel sets.

Table 3-4: Instrument Characteristics and Ice EDR Channel Applications

	SELECTED SENSOR CHANNEL SPECIFICATIONS														
Channel prefix	6		10		18		23		36		60VL	89		166	183V
Channel suffix(es)	V	H	V	H	V	H	V	H	V	H	A,…	V	H	V	A,B,C
Frequency range [GHz]	6.45-6.8		10.6-10.7		18.6-18.8		23.6-24.0		36.0-37.0		50-60	87.0-91.0		164.5-167.5	173.4-193.3
Ice EDR channel applications[1]					X	X	X	O	X	O	O	O	O	O	O
Single-sample NEDT [K]	0.47		1.2		1.3		1.1		0.66		2.8[2]	0.57		2.7	2.7[2]
20 km composite max/min NRF	--		--		0.39/		0.44/		0.48/		0.41/	0.39/		0.44/	0.40/
Earth incidence angle	55.9		58.3		53.8		53.8		55.9		55.9	55.9		55.7	55.7
Cross-scan EFOV [km]	66.5		46.8		23.1		21.3		16.9		15.0	14.9		17.4	15.5
Along-scan EFOV [km]	40.1		24.9		14.2		13.3		10.8		8.2	8.3		9.6	9.6
Integration time [ms]	5		2.5		1.2		1.2		1.2		1.2	1.2		1.2	1.2
No. EFOV per scan															
Swath width [km]															

[1] X = channel required to meet or approach threshold; O = channel used to meet or approach objectives.
[2] Figures are for lowest frequency in set. For illustrative purposes only.

3.6. Requirements for cross sensor data (NPOESS or other sensors)

The present design of the ice algorithm package does not require any data from sensors other than CMIS.

3.7. Required, alternate, and enhancing algorithm inputs

3.7.1. CMIS data and product requirements

Table 3-5: Inputs from other CMIS algorithms

CMIS Products	Usage
Spectral Emissivity from Core Module Algorithm	-Primary ice EDR retrieval input -Required at 18V, 18H, and 37V at 20 km HCS -Required at current time
Past Sea Ice Edge Location Retrieval Database	-Sea ice edge motion retrieval input -Required as vector of latitude-longitude coordinates plus observation time -Required at least twice daily per polar sector for three days prior to current time
Precipitation Flag from Core Module Algorithm	-Quality control input -Required at current time, 20 km HCS

3.7.2. Other NPOESS Sensor Data and Product Inputs

No sensor data or products are required from other NPOESS instruments.

3.7.3. External Data Requirements

Table 3-6: External data requirements

External Data	Usage
Surface Database	-Provides static surface data for land fraction algorithm inputs -Data indicates fraction of cell covered by an applicable water body (ocean or selected fresh water bodies) such that remaining fraction is composed of land or non-applicable water bodies

3.7.4. Alternate and Enhancing Data Sources

Table 3-7: Alternate and enhancing data sources

Data Source	Usage
CMIS: 18V, 18H, 22V, and 37V TBs	-Alternatives to spectral emissivity inputs

4. Algorithm description

4.1. Theoretical description of algorithm

The sea ice concentration, sea ice age-type, and fresh water ice concentration algorithm is based on experimental observations of ice and ice-type concentration effects on sensor-measured brightness temperatures. As discussed in section 3.4, these effects are similarly manifested in surface emissivities and either spectral emissivity or brightness temperatures may serve as input data to the concentration and typing algorithm. The algorithm is empirically-based and requires the specification of tuning or calibration data—called tie-points—which are the expected value of the input emissivities or TBs for scenes with 100% ice-type or water concentrations. Given the tie-points, the algorithm estimates scene ice-type and water concentrations using the position of the scene plotted on the PR-GR axis. If the inputs are brightness temperatures, additional spectral gradient threshold tests are performed that reset some weather-contaminated scenes to 100% water.

The baseline algorithm retrieves ice concentrations from emissivities retrieved by the CMIS Core Physical Inversion Module. The *ATBD for the Core Physical Inversion Module* (AER, 2000) describes this process in more detail. The Core Module removes atmospheric effects and retrieves surface effective emitting temperature T_{eff} and spectral emissivity e from top-of-atmosphere brightness temperature measurements. The Core Module uses a plane parallel model of the atmosphere whose lower boundary condition is parameterized by T_{eff} and e, where $e \equiv 1 - r$ and r is the surface specular reflectivity. Over ocean, the ice algorithm package pre-classifies the surface from brightness temperature inputs. As discussed in more detail in the next section, this pre-classification is biased toward ice false positives. If the surface is typed as ice, a background state and its error covariance matrix tuned to global, variably ice-covered ocean conditions constrain the retrieval. If the surface is typed as ice-free, a more tightly constraining ice-free ocean background is used. Over land and fresh water bodies, no pre-classification is performed and the Core Module uses a background tuned to global non-ocean conditions. The Core Module flags precipitation and passes atmospheric retrieval quality control values.

Table 4-1 summarizes algorithm design trades leading to the baseline ice algorithm design. The following sections give detailed descriptions of the mathematics of adopted trades and their role in the algorithm processing flow.

Table 4-1: Algorithm design trades

Trade Study	Baseline Decision	Basis/Benefit
Neural network retrieval from brightness temperatures	Use NASA Team approach for ice type concentration (fresh water and ocean)	NASA Team algorithm is lower risk due to operational heritage and stability of estimates. Core Module provides accurate weather effects filtering.
Emissivity-based retrieval	Support both emissivity and brightness temperature algorithm inputs. Emissivity is baseline for EDRs.	Ice concentration and type signal comes from emissivity. Core Module provides accurate emissivities (weather effects filtering). TB support required for Core Module preprocessing.
Gridding	Grid emissivity inputs and retrieve products on grid(s)	Gridded retrievals improve interaction with land-cover map, ice edge retrieval efficiency, archiving, and data access.

4.2. Mathematical Description of Algorithm

Table 4-2 defines ice algorithm inputs and other variables used in this section. The following processing steps occur prior to ice algorithm processing and are described in other documents: Derivation of CMIS brightness temperatures from raw data (*ATBD for SDR Processing*, AER, 2000); footprint matching and interpolation in the sensor reference frame (*ATBD for Common EDR Processing Tasks*, AER, 2000); Core Module retrievals of surface emissivities and effective emitting temperature (*ATBD for the CMIS Core Physical Inversion Module*, AER, 2000); and mapping of sensor-gridded data to an earth-grid (*ATBD for Common EDR Processing Tasks*, AER, 2000).

Table 4-2: Definitions of Algorithm Input and Internal Model Symbols

Algorithm Inputs	
$X_{fp} = e \text{ or } T_B$	Emissivity *or* brightness temperature at polarization p and frequency f
f_l	Fraction of land (non-water body) in retrieval cell
Other algorithm variables	
PR	Polarization ratio at 19 GHz
GR	Gradient ratio, 19-37 GHz (or 19-22 GHz as indicated)
C	Total ice concentration [fraction]
C_{FY}, C_{MY}	First-year and multi-year sea ice concentrations (Arctic)
C_A, C_B	Type A and type B sea ice concentrations (Antarctic)
C_{OW}	Open water concentration, 1 - C
C_i	Concentration of ice type i
a_i ,b_i, c_i	NASA Team algorithm parameters derived from tie point data (i = 0-3)
$f_{l,\max}$	Upper limit for land fraction correction
W_1, W_2	Weather filter thresholds for retrievals from TB
$C_{0.1}$	Ice concentration rounded to the nearest 1/10
d_e	Maximum ice edge point separation in a single segment
v_e	Maximum ice edge motion allowed

Each of the following sections provides a mathematical description of a component of the CMIS ice algorithm. Note that some components are repeated once or many times for each retrieval. Trivial components (namely, logical checks) are excluded. See Figure 4-1 for a processing flow diagram.

Ice type concentration

The algorithm calculates the concentration of two ice types using PR and GR, defined as:

$$\mathrm{PR} = \frac{X'_{19V} - X'_{19H}}{X'_{19V} + X'_{19H}} \qquad \mathrm{GR} = \frac{X'_{37V} - X'_{19V}}{X'_{37V} + X'_{19V}}. \tag{11}$$

If land is present in the retrieval cell, a land fraction correction is applied to the TBs or emissivities. Since the retrieval is performed on gridded data, the land fraction f_l for each cell is given by a static database (input). The corrected spectral data are given by:

$$X'_{fp} = \frac{X_{fp} - \max(f_l, f_{l,\max}) X_{l,fp}}{1 - \max(f_l, f_{l,\max})}. \tag{12}$$

Ice concentrations are given by the NASA Team algorithm equations (Cavalieri et al., 1984):

$$\begin{aligned} C_1 &= (a_0 + a_1\,\mathrm{PR} + a_2\,\mathrm{GR} + a_3\,\mathrm{PR}\cdot\mathrm{GR})/D \\ C_2 &= (b_0 + b_1\,\mathrm{PR} + b_2\,\mathrm{GR} + b_3\,\mathrm{PR}\cdot\mathrm{GR})/D \end{aligned} \tag{13}$$

where $D = c_0 + c_1\,\mathrm{PR} + c_2\,\mathrm{GR} + c_3\,\mathrm{PR}\cdot\mathrm{GR}$. For Arctic sea ice, $C_{FY} = C_1$ and $C_{MY} = C_2$ and in Antarctic waters $C_A = C_1$ and $C_B = C_2$. For fresh water, C_1 and C_2 are defined only by the choice of tie-points and may not represent demonstrably different ice types. C values from (13) are rounded up or down as necessary to the logical limits of 0 or 1, respectively. Total ice concentration for all regions is:

$$C = C_1 + C_2 \tag{14}$$

Weather filter

When deriving ice concentration from brightness temperatures, an addition weather filter step is performed to reduce false positive ice concentrations often retrieved over open ocean using (13):

$$C_i = 0 \textit{ if } \mathrm{GR} > W_1 \textit{ or } \mathrm{GR}(22,19) > W_2 \tag{15}$$

for all i where

$$\mathrm{GR}(22,19) = \frac{X'_{22V} - X'_{19V}}{X'_{22V} + X'_{19V}}. \tag{16}$$

W_1 and W_2 thresholds are empirical parameters to be determined in CMIS calibration efforts. For SSM/I, values of $W_1 = 0.05$ and $W_1 = 0.045$ are used (see Figure 3-1) (Cavalieri et al., 1995).

A similar weather filter is not required for emissivity-based retrievals because the Core Module effectively removes weather effects when deriving emissivities. Nevertheless, false positive ice amounts occur using (14) due to measurement noise and environmental variability in ocean and ice emissivities (detailed in section 5). For applications where even low false positive ice concentrations are undesirable, additional filtering of the retrieval product will be required.

Candidate filters include a Core Module skin temperature threshold test or tests similar to (15) but based on any of the Core Module-retrieved emissivities.

Ice age-type assignment

In the Arctic, sea ice age-type is assigned as FY according to the following criterion:

$$\text{if } C_{FY} \geq C_{MY}, \text{ ice type is FY, otherwise ice type is MY.} \qquad (17)$$

In the Antarctic, the same rule applies with the exception that A and B replace FY and MY types. Note that the ice type product is a description of the dominant type in the cell regardless of open water amount. No ice type is reported for fresh water.

Ice concentration rounding

The SRD requires fresh water ice concentration and sea ice concentration reported in increments of 0.1 or 1/10. This is accomplished by the following rounding step:

$$C_{0.1} = \text{int}(10C + 0.5)/10 \qquad (18)$$

where int(a) for $a > 0$ is the largest integer that does not exceed a.

Ice edge location

The steps above will provide total ice concentration C (not rounded to 1/10) for fresh or sea ice on an earth grid. In addition, grid cells with missing data or land will be flagged. Then the ice edge location is determined by the following steps.

1. Re-map C to a collocated 1 km (nominal) grid by interpolation between the centers of C-filled 20 km retrieval cells and extrapolation between the centers of filled 20 km cells and their edges where further filled cells are unavailable (that is, missing data, edge of swath, or land).
2. Mark each 1 km cell where at least on neighboring cell is above/below C_E, a tunable threshold value. (C_E may not necessarily be equal to the required edge threshold of 0.1 because of spatial effects and concentration retrieval bias.)
3. Of these cells, mark cells that are among the closest 3 of its neighbors to C_E.
4. Use land/water mask on 1 km (nominal) grid to exclude land points from edge.
5. Collect latitudes and longitudes of marked cells and sort into continuous segments. Break segments where the edge point jumps by more than d_e (tunable). Report ice edge segments as sequences of latitude, longitude coordinates along with the observation time.

Sea ice edge motion

Ice edge motion is reported at the coordinates of the current ice edge. The SRD does not specify a time interval for measuring ice edge displacement and any one or more previous observed ice edges may be used in the algorithm. If multiple ice displacements are calculated, the algorithm also calculates the vector-average ice velocity in km/day. The processing steps are:

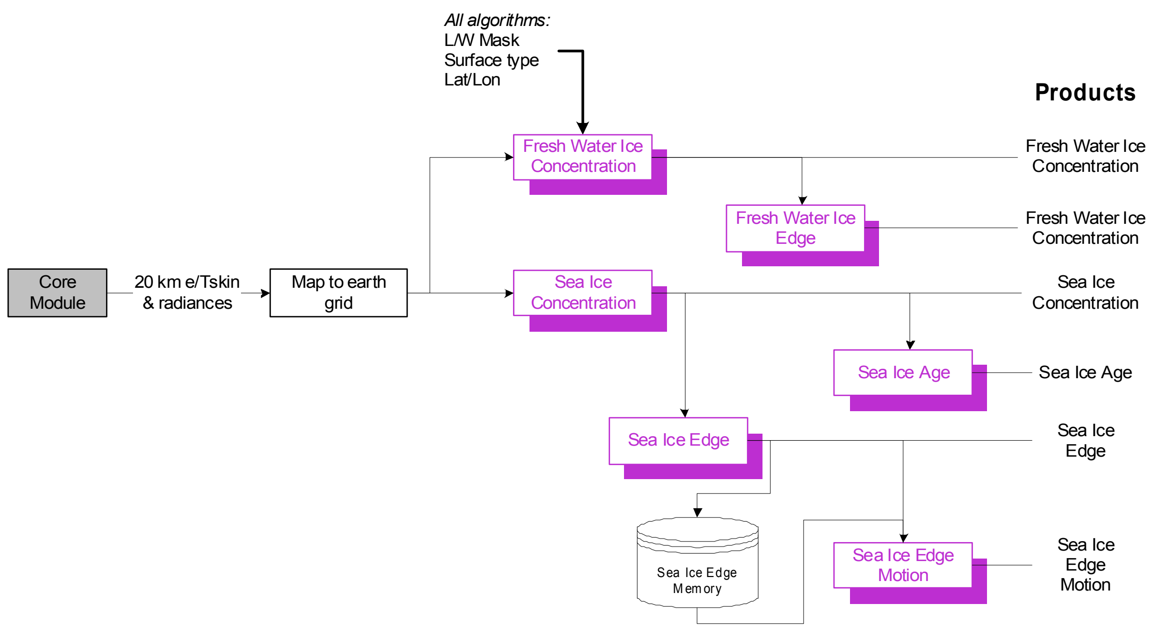
1. For each current edge-point find the closest point on the past ice edge. Treat the past ice edge as a continuous curve, interpolating between edge points as required. Ignore past ice edges in too-distant polar regions (distance will depend on time interval considered.)
2. Calculate the vector the vector (range and azimuth) from the corresponding past edge point to the current edge point. Also calculate the vector as along-meridian, along-parallel distances.
3. Remove vectors greater than v_e km/day (tunable parameter).
4. If multiple time intervals are specified, repeat 1-3 and average vectors at current ice edg points. Report vectors as speed and azimuth (or missing) at each point on the current ice edge.

4.3. Algorithm Processing Flow

4.3.1. Processing flow for CMIS ice algorithm

Figure 4-1shows the processing flow for the ice retrieval algorithm. Section 4.1 describes algorithm physics and section 4.2 gives the algorithm's mathematical description.

Figure 4-1: Ice algorithm processing flow diagram



4.4. Algorithm inputs

The table below summarizes the input data used by the ice algorithm. Input data requirements are described in more detail in section 3.7.

Table 4-3: Ice EDRs – Input Data Description

Input Data	Range
Emissivities @ 18V, 18H, 37V	0-1
Prior CMIS ice edge locations	(-90-90º latitude, -180-180º longitude)
Time of prior ice edge locations	0 - present days since reference time (for example, 0000 hr Jan. 1, 1950)
Brightness temperatures @ 18V, 18H, 22V, 37V	> 0 K
Precipitation flag	One of {0,1}
Land fractions	0-1 land (non-water body)

4.5. Algorithm products

The tables below summarize the characteristics of the operational ice EDR products.

Table 4-4: Sea Ice Concentration – Operational Product Description

Parameter	Value
Range	One of {0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1}
HCS	20 km
Units	Fraction [unitless]
QC Flag	Low Quality Input Data, Missing Data

Table 4-5: Sea Ice Age-Type – Operational Product Description

Parameter	Value
Range-Arctic	One of {FY, MY}
Range-Antarctic	One of {A, B}
HCS	20 km
Units	Ice type [unitless]
QC Flag	Low Quality Input Data, Missing Data

Table 4-6: Sea Ice Edge – Operational Product Description

Parameter	Value
Range	(-90-90, -180-180)
HCS	20 km
Units	(degrees latitude, degrees longitude)
QC Flag	Low Quality Input Data, Missing Data

Table 4-7: Sea Ice Edge Motion – Operational Product Description

Parameter	Value
Range	(0-50, 0-360)
HCS	20 km
Units	(km/day, degrees azimuth clockwise from north)
QC Flag	Low Quality Input Data, Missing Data

Table 4-8: Fresh Water Ice Concentration – Operational Product Description

Parameter	Value
Range	One of {0,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1}
HCS	20 km
Units	Fraction [unitless]
QC Flag	Low Quality Input Data, Missing Data

Table 4-9: Fresh Water Ice Edge – Operational Product Description

Parameter	Value
Range	(-90-90, -180-180)
HCS	20 km
Units	(degrees latitude, degrees longitude)
QC Flag	Low Quality Input Data, Missing Data

5. Algorithm Performance

5.1. General Description of Nominal an Limited Performance Conditions

This section describes the nominal and limited performance conditions at which the threshold requirements can be achieved. Two SRD sections address special conditions. SRDC3.2.1.1.1-4: "In the event the requirements for an EDR cannot be fully satisfied, the contractor shall identify the requirements which are not fully satisfied, and specify the conditions when they will not be satisfied." SRDC3.2.1.1.1-5: "The contractor shall also specify the conditions under which it recommends delivering an EDR which is incomplete and/or of degraded quality, but which is still of potential utility to one or more users."

The following tables describe the nominal conditions under which Threshold Requirements can be achieved or, in the case of sea ice edge motion, nominal predicted performance can be achieved.

Table 5-1: Sea Ice Concentration and Sea Ice Edge – Nominal performance characteristics

Conditions needed to meet threshold requirements	Description	Comments/Characteristics
Atmospheric condition	• Clear or cloudy • Precipitation < 1 mm/hr	Precipitation blocks signal from surface
New ice concentration	• New ice concentration < 0.2	New ice in cell changes total ice concentration signal
Land fraction	• Land fraction < 0.8	Land in cell contaminates ice concentration signal

Table 5-2: Sea Ice Age – Nominal performance characteristics

Conditions needed to meet threshold requirements	Description	Comments/Characteristics
Atmospheric condition	• Clear or cloudy • Precipitation < 1 mm/hr	Precipitation blocks signal from surface
Land fraction	• Land fraction < 0.8	Land in cell contaminates ice type signal
Ice concentration	• Ice concentration > 0.1	Low ice concentration provides insufficient ice type signal
New ice concentration	• New ice concentration < 0.8	New ice in cell changes ice type signal

Table 5-3: Sea Ice Edge Motion – Nominal performance characteristics

Conditions needed to meet threshold requirements	Description	Comments/Characteristics
Atmospheric condition	• Clear or cloudy • Precipitation < 1 mm/hr	Precipitation blocks signal from surface
Prior sea ice edge data availability	• Nominal-quality sea ice edge retrieval exists for closest edge at previous retrieval time	The edge motion product is by definition the difference between the current edge and the nearest edge at the input prior retrieval time

Table 5-4: Fresh Water Ice Concentration and Fresh Water Ice Edge – Nominal performance characteristics

Conditions needed to meet threshold requirements	Description	Comments/Characteristics
Atmospheric condition	• Clear or cloudy • Precipitation < 1 mm/hr	Precipitation blocks signal from surface
Land fraction	• Land fraction < 0.8	Land in cell contaminates ice concentration signal

The following tables describe the Limited Performance Characteristics under specific conditions; Threshold Requirements or, in the case of sea ice edge motion, nominal predicted performance may not be entirely achieved under these conditions.

Table 5-5: Sea Ice Concentration and Sea Ice Edge – Performance under limited performance conditions

Conditions	Description	Comments/Characteristics
Precipitation	Precipitation > 1 mm/hr	No retrieval
New ice concentration	New ice concentration > 0.2	Limited retrieval (degraded uncertainty)
Land fraction	• Land fraction > 0.8	Limited retrieval (degraded uncertainty)

Table 5-6: Sea Ice Age – Performance under limited performance conditions

Conditions	Description	Comments/Characteristics
Precipitation	Precipitation > 1 mm/hr	No retrieval
Land fraction	Land fraction > 0.8	Limited retrieval (degraded uncertainty)
Ice concentration	Ice concentration < 0.1	Limited retrieval (degraded uncertainty)
New ice concentration	New ice concentration > 0.8	Limited retrieval (degraded uncertainty)

Table 5-7: Sea Ice Edge Motion – Performance under limited performance conditions

Conditions	Description	Comments/Characteristics
Precipitation	Precipitation > 1 mm/hr	No retrieval
Prior sea ice edge data availability	Nominal-quality sea ice edge retrieval does not exist for closest edge at previous retrieval time	Limited retrieval (provides retrievals at other previous retrieval times)

Table 5-8: Fresh Water Ice Concentration and Fresh Water Ice Edge – Performance under limited performance conditions

Conditions	Description	Comments/Characteristics
Precipitation	Precipitation > 1 mm/hr	No retrieval
Land fraction	Land fraction > 0.8	Limited retrieval (degraded uncertainty)

5.2. Variance/Uncertainty Estimates

This section details ice algorithm performance estimates for each performance metric assigned to the algorithm from the following SRD attributes. For sea ice these are *Measurement Range* (*Ice Age Classes, Ice Motion, Concentration*), *Probability of Correct Typing* (*Ice Age*), and *Measurement Uncertainty* (*Ice motion, Ice Edge Location, Concentration*); for fresh water ice they are *Measurement Range* (*Concentration*), and *Measurement Uncertainty* (*Ice Edge Boundary, Ice Concentration*). Two simulation environments described in section 5.2.1—one for ice concentration and type and one for ice edge and edge motion—are the sources for quantitative performance estimates for these attributes. Additionally, real-data tests with SSM/I observations (described in section 5.5) contribute qualitative algorithm assessments where noted.

Of the remaining attributes, *Horizontal Cell Size* and *Horizontal Reporting Interval* are derived from the spatial properties of the sensor footprints, footprint compositing and interpolation performance, and grid definition; *Horizontal Coverage* is satisfied through the spacecraft orbit specification and algorithm definitions (that is, the sea ice retrieval is performed over oceans by definition and the fresh water ice retrieval is performed over specified fresh water bodies), *Mapping Uncertainty* is satisfied by spacecraft stability and instrument pointing error requirements, and *Swath Width* is met primarily through spacecraft orbit and instrument specifications and footprint compositing and interpolation performance. For related algorithm performance assessments, see the *ATBD for Footprint Matching and Interpolation* and the *ATBD for Common EDR Processing Tasks*. Note that Horizontal Cell Size is an explicit part of the assessment of measurement uncertainty and other algorithm retrieval performance metrics. That is, quantitative performance estimates represent comparisons of retrieved products and true cell-average products.

5.2.1. Algorithm simulation environment

The algorithm simulation environment consists of two separate systems, one for estimating ice concentration and age-type retrieval performance and one for ice edge retrieval performance.

Simulation of ice concentration and age-type retrievals

The ice simulation environment composes sensor footprints consisting of multiple surface types. Except for water, each type is described by an emissivity mean and standard deviation which represents the environmental variability in emissivity of that type. Multi-year ice environmental variability tests reported in the literature (e.g., Eppler et al., 1992) are significantly larger than those used here. Because we do not include any inter-channel covariance information, MY variability was reduced to about that of FY ice such that overall simulated ice concentration retrieval errors were consistent with heritage algorithms. Open water emissivity is represented by a physical model given varying surface temperature, wind speed, and salinity inputs. The following table lists the emissivity statistics for each type in the simulation.

Table 5-9: Simulated emissivity statistics (mean and standard deviation)

Surface Type	CMIS Channel		
	18H	18V	36V
First year ice[1]	0.888 ± 0.02	0.941 ± 0.02	0.955 ± 0.015
Multi year ice[1]	0.780 ± 0.02	0.850 ± 0.02	0.764 ± 0.02
New ice[2]	0.750 ± 0.02	0.940 ± 0.02	0.970 ± 0.015
Fresh water ice 1[2]	0.750 ± 0.02	0.850 ± 0.02	0.700 ± 0.015
Fresh water ice 2[1]	0.880 ± 0.02	0.970 ± 0.02	0.970 ± 0.02
Open water	0.328 ± 0.027	0.605 ± 0.012	0.693 ± 0.010
Land[3]	0.890 ± 0.007	0.970 ± 0.007	0.910 ± 0.007

[1] Eppler et al. (1992) with MY ice variability reduced from 0.08, 0.07, 0.08 to account for inter-channel covariance; [2] Hewison and English (1999); [3]mean derived from data reported in Prigent et al. (1998) for N. Hemisphere frozen terrain and standard deviation represents error due to estimation from nearby all-land cells.

5000 base cells were generated with varying fractions of ice type1, ice type 2, ice type 3 (or land), and water with type distributions roughly approximating mean annual Arctic conditions. Simulated truth cells are generated by adding normally-distributed environmental variability to the mean emissivity of each type and calculating the cell emissivity according to (1). This step is replicated 8 times for each base cell for a total of 40000 simulation cells. Then the measured emissivity is simulated by adding normally-distributed noise to the cell emissivities with specified standard deviation (given below). This noise includes spatial representativeness errors, residual atmospheric effects, and the physical errors suggested in (10). (Since land emissivity is estimated locally using nearby 100% land cells, the noise in these emissivities represents only the local emissivity variability .) The ice concentration and ice age algorithms are applied to the simulated emissivity measurements and retrieval performance statistics are calculated by comparing retrieval products to corresponding true scene data.

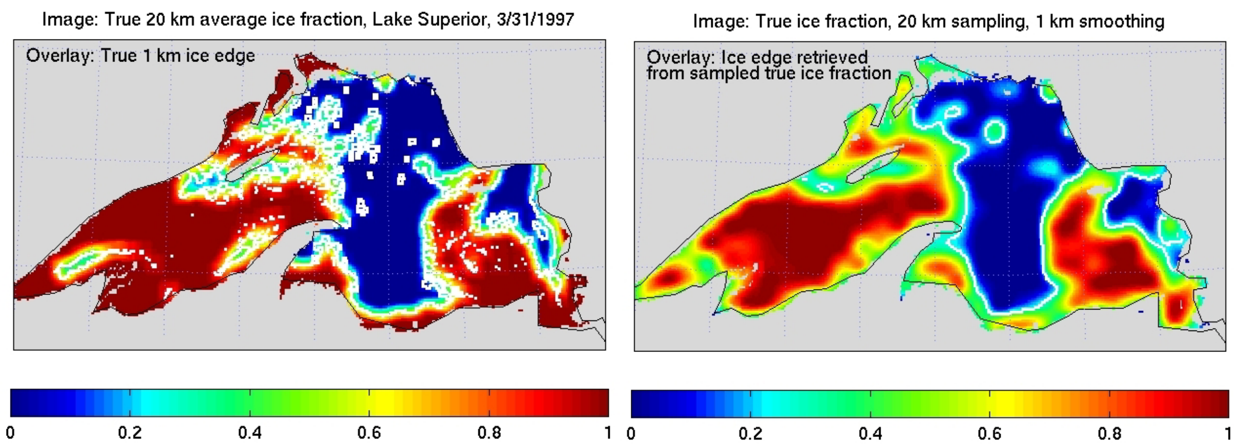
The following combinations of types were tested in separate implementations of the simulation described above: 1) FY, MY, and open water, 2) FY, MY, new ice, and open water, 3) FY, MY, land, and open water, and 4) Fresh water ice type 1, fresh water ice type 2, land, and open water..

Note that sea water simulations were used for fresh water ice retrievals as well with the assumption that retrieval statistics are comparable for both.

Simulation of ice edge retrievals

Ice edge retrievals were simulated using a ~1 km resolution AVHRR image of Lake Superior classified as ice, water, and land. Any water pixels off the lake were reclassified as land and the same image served as a 1 km land mask. The true ice edge water was plotted based on the 1 km imagery and the true 20 km average ice concentration was calculated around each 1 km cell (Figure 5-1). Ice concentration measurements were simulated by adding normally-distributed noise with specified variance to true ice concentrations sampled with 20 km horizontal reporting interval. The ice edge algorithm was then applied to the simulated measurements and the process was repeated five times to generate a sufficient ensemble of noise realizations. As specified in the SRD, the ice edge error was calculated at each point on the retrieved ice edge as the distance between the point and the nearest point on the true ice edge. This definition is deficient in the sense that false negatives are not penalized—if no ice edge is retrieved where one exists there is no impact on the measurement error. For example, in the images below there is no ice edge detected from the 20 km ice concentration data that corresponds to the large areas of open water in the south-western end of Lake Superior. In the future, a more descriptive performance metric may be implemented.

Figure 5-1: Ice edge and ice concentration simulation



5.2.2. Binning Categories

Variance and uncertainty estimates are stratified by reporting performance in bins. Each bin represents a range of values for a particular environmental condition. Table 5-10 lists the bin categories and the environment parameter range for each bin. Typically, when measurement uncertainty is reported as a function one of these parameters, the other parameters are held in their default range. This keeps the number of uncertainty estimates at a manageable level.

Table 5-10: Measurement uncertainty environmental parameter bins

Bin Category	Ice conc.	FY ice conc.	MY ice conc.	New ice conc.	Land fraction
Default range	0-1	0-1	0-1	0	0
Default range for sea ice type	0.1-1	0-1	0-1	0	0
Bin ranges	0 0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1 1	0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1	0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1	0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1	0-0.2 0.2-0.4 0.4-0.6 0.6-0.8 0.8-1

5.2.3. Measurement Uncertainty Performance

The following tables summarize measurement uncertainty estimates stratified for a variety of environmental conditions. The tables give measurement uncertainty results directly from the simulation environment (described in section 5.2.1). As described in section 5.3, no additional adjustments are added based on a measurement budget. This is shown explicitly only in Table 5-11.

5.2.3.1 Sea ice concentration measurement uncertainty

Table 5-11: Sea ice concentration measurement uncertainty by concentration range

Environmental Categories - Baseline Bins					No. in Sim. Bin	Meas. Uncertainty		
Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates	Required
0	0-1	0-1	0	0	14160	0.049	0.049	0.100
0-0.2	0-1	0-1	0	0	2336	0.052	0.052	0.100
0.2-0.4	0-1	0-1	0	0	2344	0.052	0.052	0.100
0.4-0.6	0-1	0-1	0	0	2360	0.049	0.049	0.100
0.6-0.8	0-1	0-1	0	0	2424	0.060	0.060	0.100
0.8-1	0-1	0-1	0	0	2312	0.067	0.067	0.200
1	0-1	0-1	0	0	14064	0.058	0.058	0.200

Table 5-12: Sea ice concentration measurement uncertainty by environmental category

Environmental Categories					No. in Sim. Bin	Meas. Uncertainty	
Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates
0-1	0	0-1	0	0	18696	0.052	0.052
0-1	0-0.2	0-1	0	0	3808	0.055	0.055
0-1	0.2-0.4	0-1	0	0	3248	0.051	0.051
0-1	0.4-0.6	0-1	0	0	3168	0.048	0.048
0-1	0.6-0.8	0-1	0	0	2896	0.057	0.057
0-1	0.8-1	0-1	0	0	2696	0.066	0.066
0-1	1	0-1	0	0	5488	0.060	0.060

Environmental Categories					No. in Sim. Bin	Meas. Uncertainty	
Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates
0-1	0-1	0	0	0	28496	0.054	0.054
0-1	0-1	0-0.2	0	0	2328	0.055	0.055
0-1	0-1	0.2-0.4	0	0	1656	0.050	0.050
0-1	0-1	0.4-0.6	0	0	1216	0.049	0.049
0-1	0-1	0.6-0.8	0	0	1248	0.054	0.054
0-1	0-1	0.8-1	0	0	992	0.062	0.062
0-1	0-1	1	0	0	4064	0.062	0.062

Environmental Categories					No. in Sim. Bin	Meas. Uncertainty	
Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates
0-1	0-1	0-1	0	0	28536	0.055	0.055
0-1	0-1	0-1	0-0.2	0	3936	0.086	0.086
0-1	0-1	0-1	0.2-0.4	0	2320	0.206	0.206
0-1	0-1	0-1	0.4-0.6	0	1464	0.326	0.326
0-1	0-1	0-1	0.6-0.8	0	1096	0.467	0.467
0-1	0-1	0-1	0.8-1	0	1112	0.645	0.645
0-1	0-1	0-1	1	0	1536	0.818	0.818

Environmental Categories					No. in Sim. Bin	Meas. Uncertainty	
Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates
0-1	0-1	0-1	0	0	28536	0.055	0.055
0-1	0-1	0-1	0	0-0.2	3936	0.053	0.053
0-1	0-1	0-1	0	0.2-0.4	2320	0.054	0.054
0-1	0-1	0-1	0	0.4-0.6	1464	0.064	0.064
0-1	0-1	0-1	0	0.6-0.8	1096	0.060	0.060
0-1	0-1	0-1	0	0.8-1	1112	0.110	0.110

5.2.3.2 Fresh water ice concentration measurement uncertainty

Table 5-13: Fresh water ice concentration measurement uncertainty by concentration

Category		No. in Sim. Bin	Meas. Uncertainty		
Range	Land Fraction		Simulation	Simulation + Budget Estimates	Required
0	0	13976	0.053	0.053	0.100
0-0.2	0	880	0.052	0.052	0.100
0.2-0.4	0	816	0.053	0.053	0.100
0.4-0.6	0	928	0.053	0.053	0.100
0.6-0.8	0	672	0.069	0.069	0.100
0.8-1	0	808	0.073	0.073	0.200
1	0	10456	0.062	0.062	0.200

Table 5-14: Fresh water ice concentration measurement uncertainty by land fraction

Category		No. in Sim. Bin	Meas. Uncertainty	
Range	Land Fraction		Simulation	Simulation + Budget Estimates
0-1	0	28536	0.058	0.058
0-1	0-0.2	3936	0.058	0.058
0-1	0.2-0.4	2320	0.059	0.059
0-1	0.4-0.6	1464	0.068	0.068
0-1	0.6-0.8	1096	0.065	0.065
0-1	0.8-1	1112	0.112	0.112

5.2.4. Probability of correct typing performance

The following tables summarize sea ice age-type probability of correct typing estimates stratified for ice concentration and ice type. The tables give results directly from the simulation environment (described in section 5.2.1). As described in section 5.3, no additional adjustments are added based on a measurement budget.

Table 5-15: Sea ice age probability of correct typing by ice concentration

Environmental Categories				No. in Bin	Overall Prob. of Correct Typing [%]		
Total Ice Conc.	Ice Type	New Ice Conc.	Land Fraction		Simulation	95% Confidence Interval	Required
0-0.1	FY/MY	0	0	927	65	3	>70
0.1-0.2	FY/MY	0	0	1152	73	3	>70
0.2-0.4	FY/MY	0	0	2344	87	2	>70
0.4-0.6	FY/MY	0	0	2360	91	2	>70
0.6-0.8	FY/MY	0	0	2424	91	2	>70
0.8-1	FY/MY	0	0	2312	92	1	>70
1	FY/MY	0	0	14064	91	1	>70

Table 5-16: Sea ice age probability of correct typing by ice concentration and type

Environmental Categories				No. in Bin	FY Probability of Correct Typing [%]		
Total Ice Conc.	Ice Type	New Ice Conc.	Land Fraction		Simulation	95% Confidence Interval	Required
0-0.1	FY	0	0	801	65	3	>70
0.1-0.2	FY	0	0	1008	74	3	>70
0.2-0.4	FY	0	0	1992	88	2	>70
0.4-0.6	FY	0	0	2080	92	2	>70
0.6-0.8	FY	0	0	2096	93	1	>70
0.8-1	FY	0	0	1968	93	1	>70
1	FY	0	0	7760	91	1	>70

Environmental Categories				No. in Bin	MY Probability of Correct Typing [%]		
Total Ice Conc.	Ice Type	New Ice Conc.	Land Fraction		Simulation	95% Confidence Interval	Required
0-0.1	MY	0	0	126	64	8	>70
0.1-0.2	MY	0	0	144	69	7	>70
0.2-0.4	MY	0	0	352	78	4	>70
0.4-0.6	MY	0	0	280	81	5	>70
0.6-0.8	MY	0	0	328	80	4	>70
0.8-1	MY	0	0	344	83	4	>70
1	MY	0	0	6304	90	1	>70

Table 5-17: Sea ice age probability of correct typing by environmental category

Environmental Categories				No. in Bin	Overall Prob. of Correct Typing [%]		
Total Ice Conc.	Ice Type	New Ice Conc.	Land Fraction		Simulation	95% Confidence Interval	Required
0.1-1	FY/MY	0	0	14096	90	1	>70
0.1-1	FY/MY	0-0.2	0	2640	86	2	>70
0.1-1	FY/MY	0.2-0.4	0	1575	87	2	>70
0.1-1	FY/MY	0.4-0.6	0	989	81	3	>70
0.1-1	FY/MY	0.6-0.8	0	693	81	3	>70
0.1-1	FY/MY	0.8-1	0	631	63	4	>70

Environmental Categories				No. in Bin	Overall Prob. of Correct Typing [%]		
Total Ice Conc.	Ice Type	New Ice Conc.	Land Fraction		Simulation	95% Confidence Interval	Required
0.1-1	FY/MY	0	0	14101	90	1	>70
0.1-1	FY/MY	0	0-0.2	2571	87	2	>70
0.1-1	FY/MY	0	0.2-0.4	1446	92	2	>70
0.1-1	FY/MY	0	0.4-0.6	923	90	2	>70
0.1-1	FY/MY	0	0.6-0.8	576	87	3	>70
0.1-1	FY/MY	0	0.8-1	438	59	4	>70

The formula for calculating probability of correct typing flows from the SRD definition. Given a set of observations and corresponding truth, the probability of correct typing for type i is:

$$100*\mathrm{sum}(\text{retrieved type} = i \ \& \ \text{true type} = i) \div \mathrm{sum}(\text{retrieved type} = i). \tag{19}$$

Since the range of retrieved types is FY or MY, the definition does not provide a performance penalty for excluding either type when ice is present—the result when retrieved ice concentration is zero. (Conversely, there is a penalty for providing an ice type when the true ice concentration is zero, highlighted in the 0 ice concentration category above.) Misidentification of ice is treated by ice concentration measurement uncertainty performance. The minimum retrieved ice concentration for which an ice type is returned is a tunable algorithm parameter that depends on the user's tolerance for false positive or negative ice type retrievals.

5.2.5. Fresh water ice edge and sea ice edge measurement uncertainty

Ice edge measurement uncertainty is estimated using the ice edge simulation environment described above. Since the primary input parameter is ice concentration, no further stratification of the results will be provided here. Note that with zero ice concentration error, the resulting simulated ice edge measurement uncertainty is about 4.4 km.

- The estimated sea ice concentration error for low ice concentrations is 0.053. The simulated sea ice edge measurement uncertainty with this ice concentration error is 4.7 km. Assuming 3 km mapping uncertainty, the total predicted **sea ice edge measurement uncertainty** is found by as the square-root of the sum of squares: 5.6 km (TBD threshold requirement).
- The estimated fresh water ice concentration error for low ice concentrations is also about 0.053. The simulated fresh water ice edge measurement uncertainty with this error is 4.7 km. Assuming 3 km mapping uncertainty, the total predicted **fresh water ice edge measurement uncertainty** is found by as the square-root of the sum of squares: 5.6 km (10 km threshold requirement).

5.2.6. Sea ice edge motion measurement uncertainty

Sea ice edge motion is estimated based on the estimated error in ice edge location (given above). Given a set of N intervals Δt_i over which sea ice edge motion at the current observation is calculated and assuming that the ice edge retrieval error at all times is the same (σ_e) and that the errors at each time and in each direction are uncorrelated, then the sea ice edge motion error is approximately

$$\frac{\sigma_e}{N}\left[\sum_{i=1}^{N}\frac{1}{(\Delta t_i)^2}\right]^{1/2}. \tag{20}$$

Since ice concentration is the primary input to ice edge motion (via ice edge) and its performance has been fully stratified above, no further stratification by environmental conditions will be provided here. The table below gives ice edge motion retrieval error performance as a function of time interval for single edge comparisons and multiple edge comparisons (assuming up to 6 evenly-spaced observations per day). The single comparisons are to edge retrievals at 1, 2, 3, and 4 days prior to the current time. More than a five day interval is needed to meet the 1 km/day threshold measurement uncertainty requirement with a single comparison. The multiple comparisons are to three or six edge retrievals within the given intervals. If three edge retrievals per day are available, then threshold performance is just achieved using a 3-4 day interval. Performance improves to 0.64 km/day if six previous edge retrievals are available in the interval (possible in at least some parts of the polar regions when CMIS is operating on two platforms). Selection of the time period and intervals will depend on user preferences.

Table 5-18: Sea ice edge motion measurement uncertainty by overall time interval with and without averaging of multiple comparisons

Time Period [days before current time]	Measurement Uncertainty [km/day]			
	Single Comparison	Three Comparisons per Period	Six Comparisons per Period	Requirement
0-1	5.60	6.53	6.80	1
1-2	2.80	2.02	1.52	1
2-3	1.87	1.23	0.90	1
3-4	1.40	0.89	0.64	1
4-5	1.12	0.69	0.50	1

5.2.7. Measurement Range Performance

By algorithm definition, the measurement range for ice concentration is 0-1, ice type first year and multi-year, and ice motion 0-50 km/day. The performance estimates in section 5.2.3 show that measurement performance requirements for each product are met over the full measurement ranges required for that product under nominal conditions (summarized in section 5.1).

5.3. Sensitivity Studies

The tables below demonstrate how ice concentration retrieval uncertainty degrades with emissivity measurement error. Sea ice and fresh water ice concentration measurement uncertainty meet requirements at 0.0075 emissivity error under nominal conditions. Consequently, there is considerable margin in emissivity retrieval performance.

Table 5-19: Sea ice concentration measurement uncertainty by emissivity retrieval error

Emissivity Retrieval RMS Error	Environmental Categories					No. in Sim. Bin	Meas. Uncertainty		
	Range	FY Ice Conc.	MY Ice Conc.	New Ice Conc.	Land Fraction		Simulation	Simulation + Budget Estimates	Required
0	0.4-0.6	0-1	0-1	0	0	14160	0.046	0.046	0.100
0.005	0.4-0.6	0-1	0-1	0	0	14160	0.049	0.049	0.100
0.0075	0.4-0.6	0-1	0-1	0	0	14160	0.052	0.052	0.100
0	0-1	0-1	0-1	0	0	28536	0.053	0.053	0.100
0.005	0-1	0-1	0-1	0	0	28536	0.055	0.055	0.100
0.0075	0-1	0-1	0-1	0	0	28536	0.056	0.056	0.100
0	0-1	0-1	0-1	0.4-0.6	0	3936	0.327	0.327	0.100
0.005	0-1	0-1	0-1	0.4-0.6	0	3936	0.326	0.326	0.100
0.0075	0-1	0-1	0-1	0.4-0.6	0	3936	0.325	0.325	0.100
0	0-1	0-1	0-1	0	0.4-0.6	1464	0.060	0.060	0.100
0.005	0-1	0-1	0-1	0	0.4-0.6	1464	0.064	0.064	0.100
0.0075	0-1	0-1	0-1	0	0.4-0.6	1464	0.068	0.068	0.100

Table 5-20: Fresh water ice concentration measurement uncertainty by emissivity retrieval error

Emissivity Retrieval RMS Error	Category		No. in Sim. Bin	Meas. Uncertainty		
	Range	Land Fraction		Simulation	Simulation + Budget Estimates	Required
0	0.4-0.6	0	13976	0.048	0.048	0.100
0.005	0.4-0.6	0	13976	0.053	0.053	0.100
0.0075	0.4-0.6	0	13976	0.056	0.056	0.100
0	0-1	0	28536	0.056	0.056	0.100
0.005	0-1	0	28536	0.058	0.058	0.100
0.0075	0-1	0	28536	0.059	0.059	0.100
0	0-1	0.4-0.6	1464	0.064	0.064	0.100
0.005	0-1	0.4-0.6	1464	0.068	0.068	0.100
0.0075	0-1	0.4-0.6	1464	0.073	0.073	0.100

Table 5-19 and Table 5-20 also delineate the contributions of emissivity measurement error and environmental noise to the total concentration retrieval error. That is, with zero emissivity retrieval error, measurement uncertainty is entirely due to environmental variability—the differences between the emissivities of each ice type in the tie-point data used for algorithm calibration and the true emissivities present. As stated below, we assume that retrieval performance is based on the use of appropriate emissivity tie points for the time of year and region of algorithm application. Extreme emissivity errors have been accounted for by new ice and land fraction categories. Most other ice emissivity errors are included in the variability of the two principle ice types, although special cases such as melt-ponds or Antarctic ice types may be considered separately in the future. Since this analysis includes errors due spatial heterogeneity, emissivity measurement, algorithm assumptions, and surface environmental variability, we do not incorporated additional error budget contributions to our performance predictions.

5.4. Constraints, Limitations, and Assumptions

- As stated in section 3.2.2, the definition of ice edge given for the sea ice EDR applies to the fresh water ice EDR. That is, for fresh water ice: An ice edge is defined as the boundary between ice-covered fresh water (ice concentration > 0.1) and fresh water not covered by ice (ice concentration ≤ 0.1). This definition flows into algorithm parameters to be specified through calibration efforts. A change in the ice edge definition could be accommodated when the algorithm is calibrated.
- We assume that ice emissivity tie-points appropriate to the region and season are provided to the algorithm. Tie points will be derived as a part of calibration and validation efforts. Local tie points for open water may be taken from emissivity retrievals in nearby ice free pixels when available.
- Our simulations are based on natural surface emissivity with surface-type dependent mean values and variability that is both normally-distributed and independent in each channel (see Table 5-9). Comparison of Figure 3-1 and Figure 3-2 suggests that the assumption of channel noise independence distorts variability in the PR and GR functions such that, if observed ice emissivity variability were used, the simulation would over-estimate retrieval uncertainty. Therefore, simulated emissivity variability is set to a value less than that reported in the literature from experimental observations. Specifically, MY ice standard deviation is reduced from the 0.07-0.08 range to 0.02. This value was chosen so that overall

ice concentration retrieval uncertainty—about 0.05—was consistent with SSM/I validation of the NASA Team Algorithm *without* atmospheric correction—about 0.038-0.075 (Cavalieri and Comiso, 2000). Our results demonstrate some added value of the Core Module's atmospheric correction through expanding the measurement range to low ice concentrations. However, the simulation setup does not fully expose any additional benefits that might accrue to overall performance.

5.5. Algorithm performance tests with similar sensor data

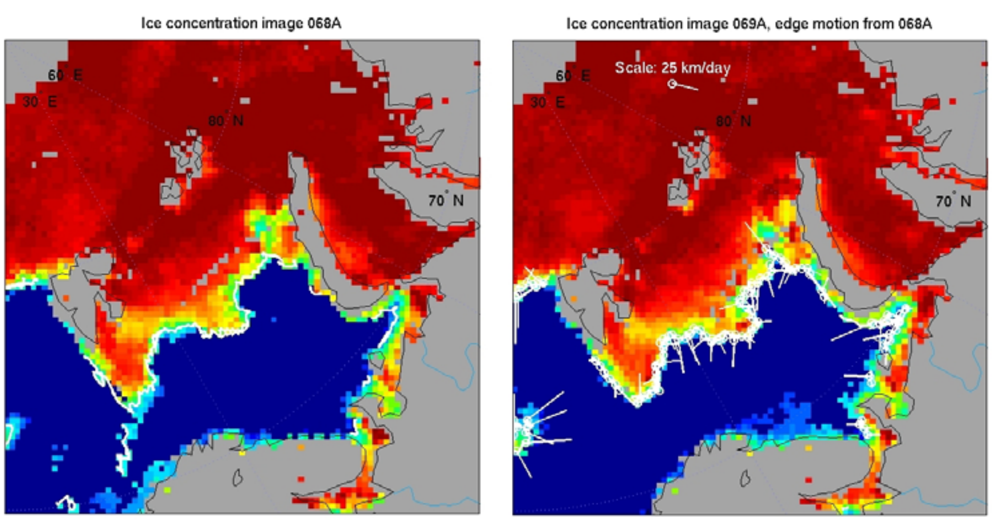
5.5.1. SSM/I sea ice edge motion retrieval test

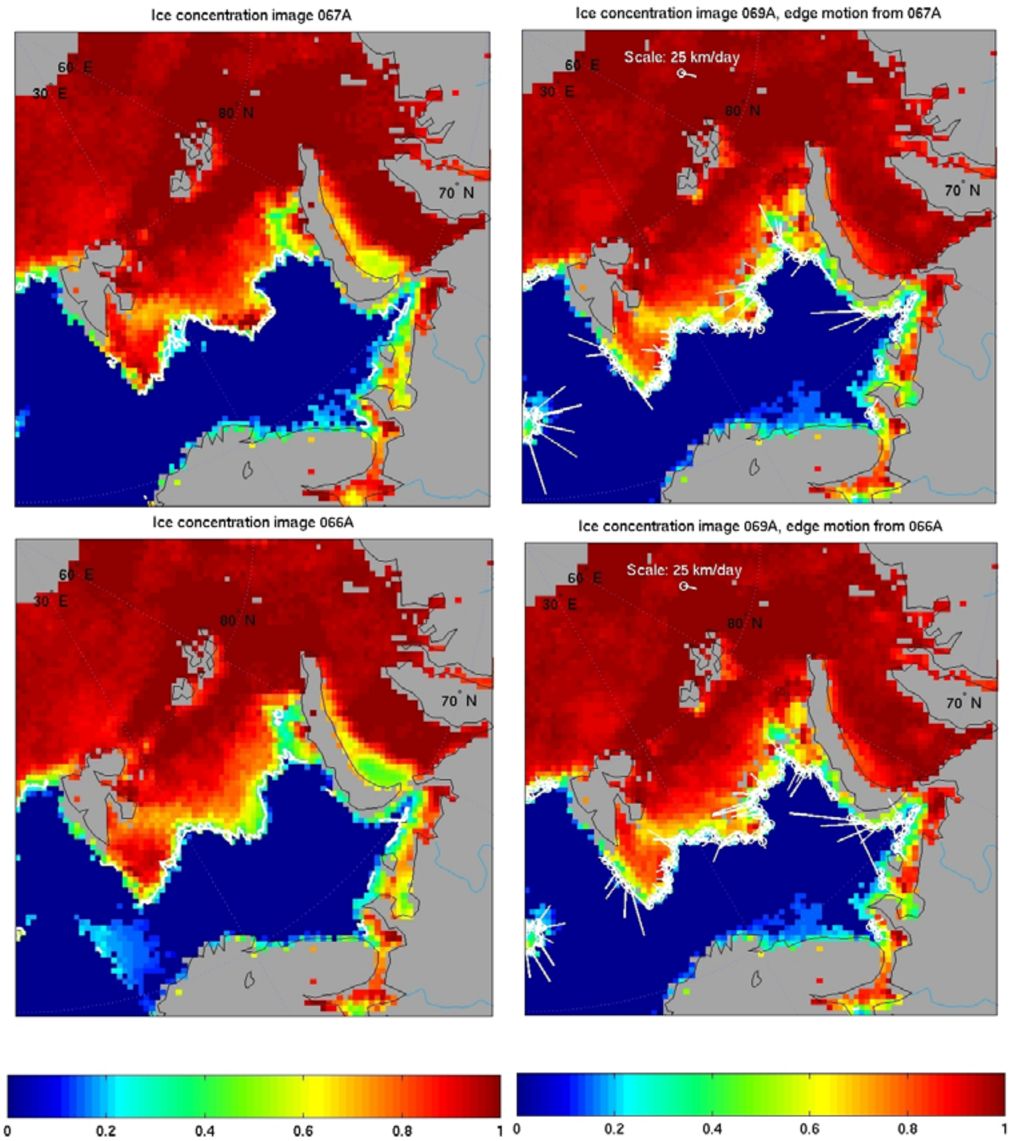
The sea ice edge motion algorithm was applied to the SSM/I scenes summarized in Table 5-21. We applied the brightness temperature version of the ice concentration algorithm to gridded brightness temperatures for several observation times, then applied the ice edge algorithm to the ice concentration images, and the ice edge motion algorithm to sets of ice edge data from separate days. Figure 5-2 shows ice edge motion retrievals for the day 69, ascending node, with 1, 2, and 3 day intervals from the past edge observation time. Ice concentration and edge retrievals are self-consistent and consistent among the three days. Edge motion vectors are similar on each day with velocities somewhat larger with 3-day (day 66-69) separation. (Note the change in vector scale between the three images.) Smoothing of the vectors may be achieved by averaging the vectors from the three intervals and others as available (not shown).

Table 5-21: Sea ice test scene summary

Region	Barents Sea
SSM/I data collected	Day 61-70, 1993
SSM/I format	EASE-Grid with one file per node per day
Edge motion retrieval time	Day 69, ascending node
Previous times used	Days 66, 67, 68, ascending nodes

Figure 5-2: Sea edge motion retrievals with 1, 2, and 3 day intervals





5.5.2. SSM/I fresh water ice concentration retrieval tests

The fresh water ice algorithm was applied to four SSM/I scenes matched to a single "truth" scene derived from ~1 km AVHRR data. Figure 5-1 shows 20 km ice concentration evaluated from the 1 km data. Since SSM/I, not CMIS, is used here, 50 km-averaged ice concentration is used (Figure 5-8). The table below summarizes the four SSM/I scenes used in the test. Of these, only scenes 90D and 91 D which have complete coverage of the lake are evaluated in detail

Table 5-22: Fresh water ice test scene summary

Region	Lake Superior			
Source of truth scene	AVHRR			
Date and time of truth scene	Day 90, 1997, 1843 hr UTC			
SSM/I format	EASE-Grid with one file per node per day			
SSM/I scenes (day and node)	90D	90A	91D	91A
Time stamp [same day UTC]	1210	2440	1235	2355

Figure 5-3 shows sensitivities of PR, GR, and PR*GR to ice concentration (all orbits) and retrieved vs. true ice concentration for orbits 90D and 91D. Each parameter has some sensitivity to ice concentration but there is no one that clearly maps to ice concentration. Much of the spread is attributable to errors in evaluating the AVHRR truth scene, changes in ice cover between the truth scene and the SSM/I scenes, and contamination by land, geolocation error, and sensor footprint shape. RMS error of the baseline algorithm (discussed below) is 0.3 for scenes 90D and 91D. Because of the unknown impact the external error sources, the following discussion focuses primarily on qualitative observations about the algorithm and retrieval performance.

Figure 5-3: Sensitivity of SSM/I PR, GR, and PR*GR to ice concentration (all orbits) and retrieved vs. true ice concentration for orbits 90D and 91D (baseline method).

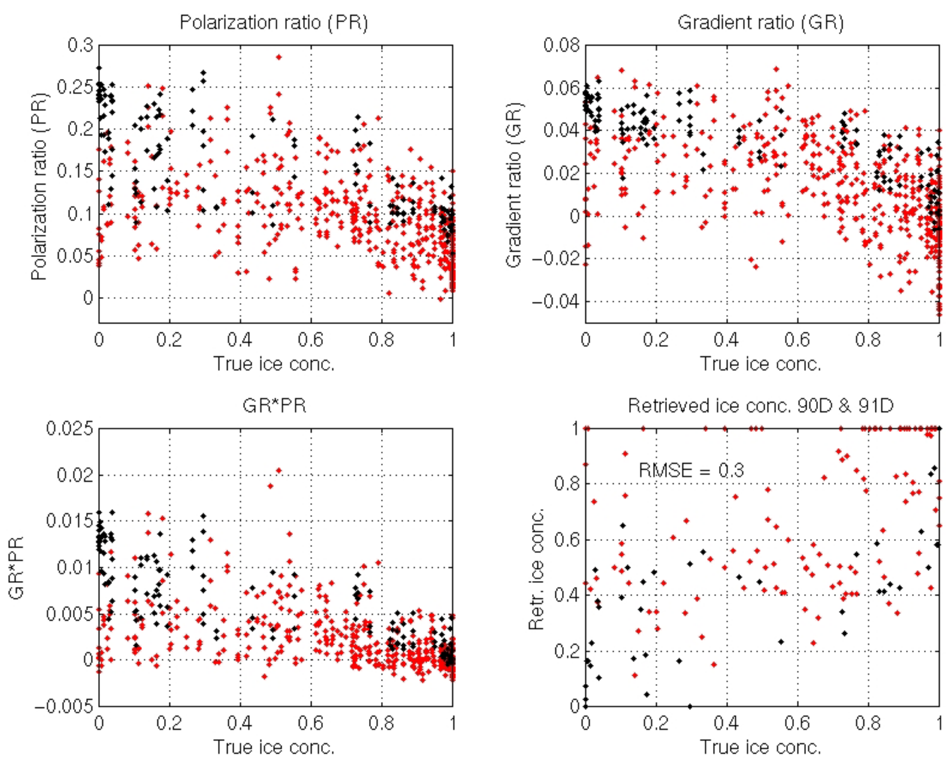
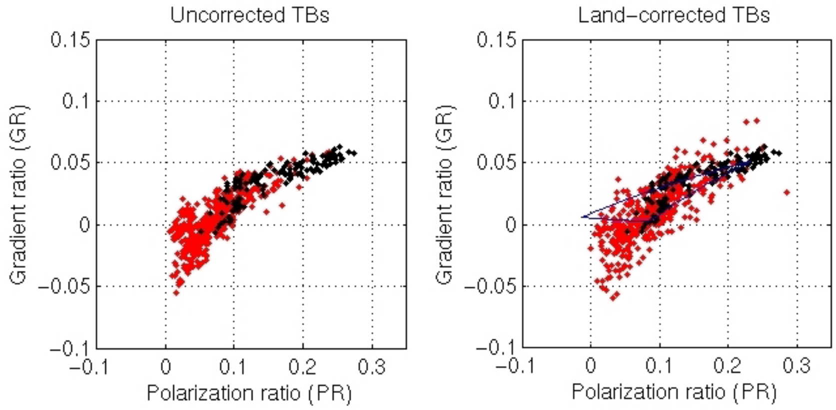


Figure 5-4 show the PR-GR scatter plots for TBs with and without correction for land contamination (equation 12 with $f_{l,max}$ = 0.5). Note that the red land-corrected data—black points have zero land fraction—are more scattered than uncorrected. Taken with simulation results where optimum measurement uncertainty was achieved with $f_{l,max}$ = 0.25, the increased scatter suggests that in some cases TBs have been over-corrected. The selection of $f_{l,max}$ is a balance between reducing land-contamination noise and limiting the added noise of uncertain land emissivity estimates. Calibration/validation efforts will provide an opportunity for further refinement of $f_{l,max}$.

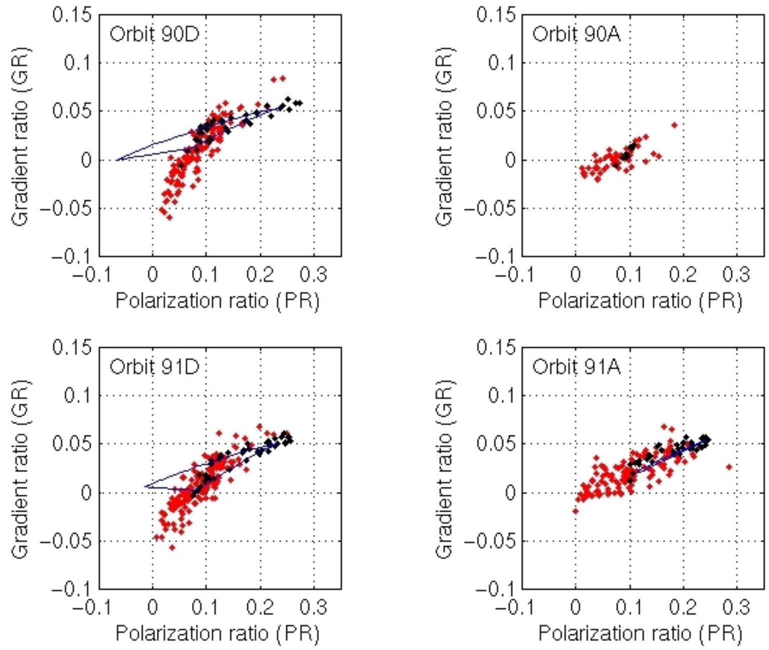
Figure 5-4: PR-GR scatter plots for all orbits from SSM/I TBs uncorrected (left) and corrected (right) for partial land contamination.



The ice triangle plotted in Figure 5-4 is based on tie-points inferred from orbit 91D data. The open water tie point was calculated by averaging TB data (19H, 19V, and 37V) from areas that were closest to 100% open water in the truth scene with no land contamination. The first ice tie-point was selected subjectively from pixels closest to 100% ice. The second ice tie-point was selected from a pixel with about 20% ice cover. The TB of that ice type was found by correcting for the true ice fraction using an equation similar to (12). We chose this tie-point in a effort to isolate a second ice type common to sparse ice regions. In general, the tie-points should represent the mean TB (or emissivity) of an identified ice type. Tie-point definition will be a key area for future algorithm tuning efforts.

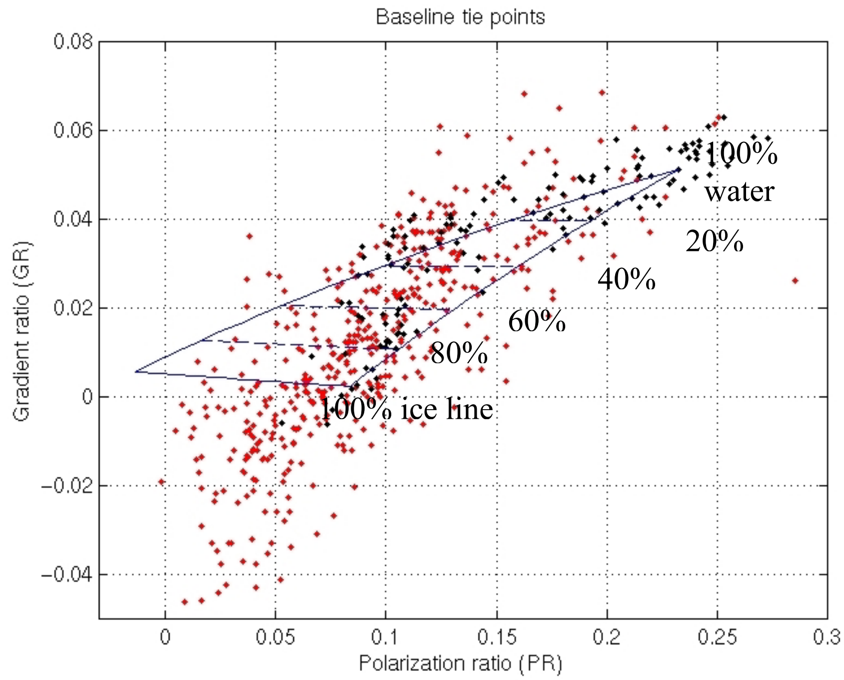
Figure 5-5 shows PR-GR scatterplots for each SSM/I scene overlaid with the ice triangle derived for that scene. Orbit 90A and 91A do not provide adequate data for triangle definition. Note that in orbits 90D and 91D many point have GR values that put them well below the ice triangle. This may be due to an unidentified ice type or to land contamination. Land contamination is suggested by the fact that the non-land contaminated pixel (black) do not fall in this region. Also, since wintertime land surfaces frequently have scattering surfaces, low GR is expected for land. Also likely, however, is that there is a separate ice type near land with low GR due possibly to age, structure, or accumulated snow cover.

Figure 5-5: PR-GR scatterplots from land-corrected TBs with ice tie-point triangles from baseline tie-point method for each orbit (overlay, except orbit 90A).



To test the hypothesis that near-land ice has a distinct spectral signature, we calculated a second set of ice tie points: Type 1 has PR close to 0 and GR close to 0.1, and type 2 has $f_l > 0.5$ and true ice concentration near 1. Figure 5-6 compares the baseline and alternative ice triangles. The alternative triangle appears to be more similar of the two to the FY-MY-OW sea ice triangle while the baseline is similar to FY-NEW-OW triangles.

Figure 5-6: Tie-point triangles plotted with data from all orbits. Top: Baseline tie-point method from orbit 91D. Bottom: Alternative tie-points from orbit 90D.



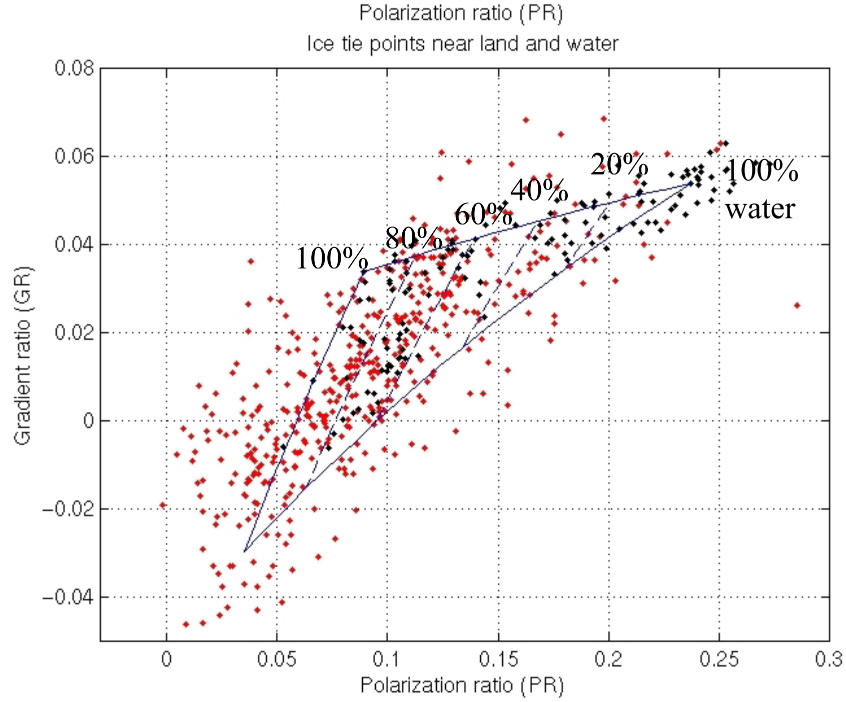


Figure 5-9 show Figure 5-10 ice concentration retrieval tests with the baseline and alternative tie-points, respectively. Figure 5-7 shows the static input data (gridded water body fraction and cell type) and Figure 5-8 shows the true ice concentration from AVHRR. The total lake concentration for the truth and all retrievals is about the same (0.55) except for the alternative retrieval for orbit 90D which is much higher (0.7). The baseline tie-points with day 91 data seems to give the best fit to the truth imagery and the baseline method is most consistent between the two days.

Figure 5-7: Static water body fraction and cell type data for Lake Superior.

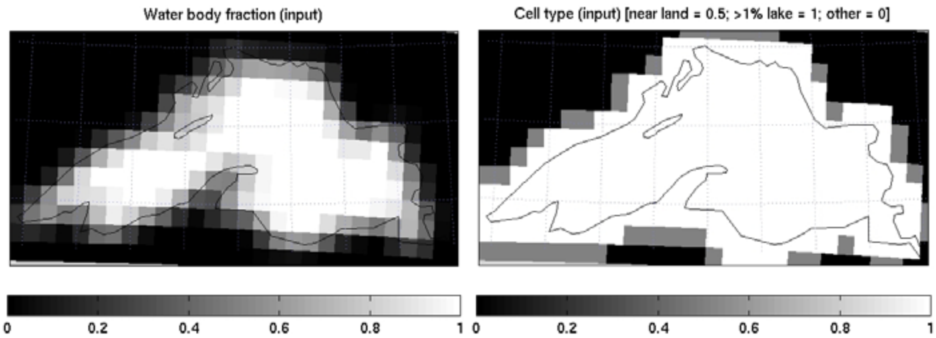


Figure 5-8: 50 km true ice concentration from ~1 km AVHRR imagery.

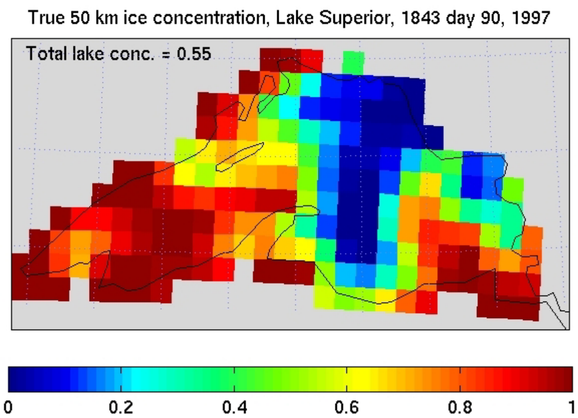


Figure 5-9: Ice concentration retrieved from SSM/I TBs using baseline tie-points.

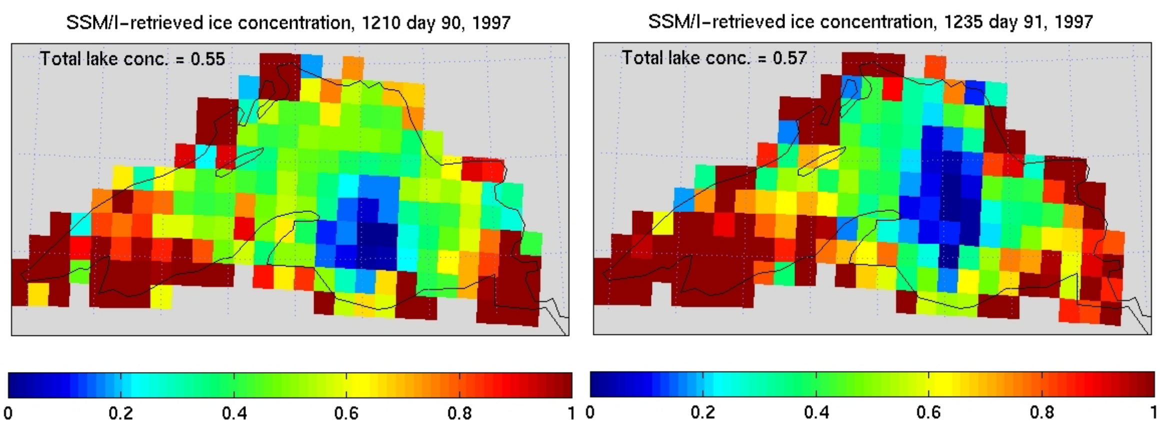
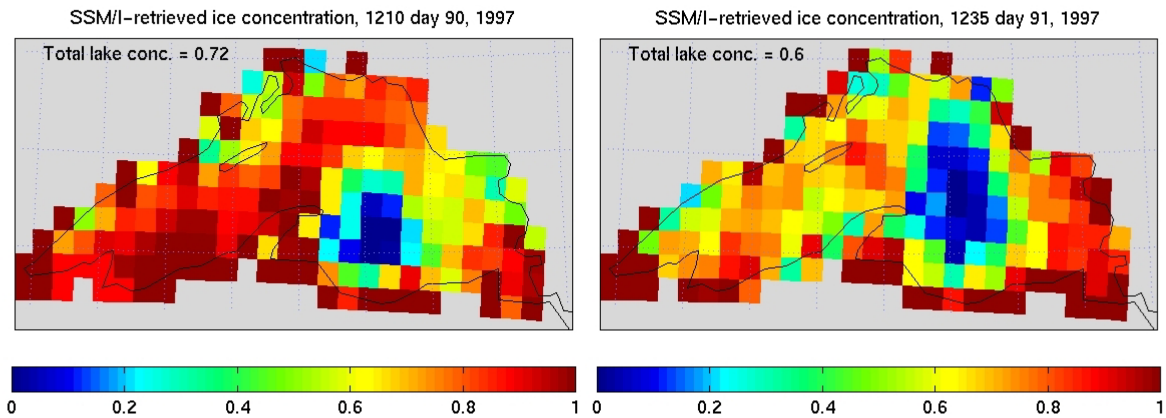


Figure 5-10: Ice concentration retrieved from SSM/I TBs using alternative tie-points.



6. Algorithm Calibration and Validation Requirements

6.1. Pre-launch

To be completed.

6.2. Post-launch

To be completed.

6.3. Special considerations for Cal/Val

To be completed.

6.3.1. Measurement hardware

To be completed.

6.3.2. Field measurements or sensors

To be completed.

6.3.3. Sources of truth data

To be completed.

7. Practical Considerations

7.1. Numerical Computation Considerations

To be completed.

7.2. Programming/Procedure Considerations

To be completed.

7.3. Computer hardware or software requirements

To be completed.

7.4. Quality Control and Diagnostics

To be completed.

7.5. Exception and Error Handling

To be completed.

7.6. Special database considerations

To be completed.

7.7. Special operator training requirements

To be completed.

7.8. Archival requirements

To be completed.

8. Glossary of Acronyms

AMSR	Advanced Microwave Scanning Radiometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
BT	Brightness Temperature [K]
CMIS	Conical Microwave Imaging Sounder
DEM	Digital Elevation Model
DMSP	Defense Meteorological Satellite Program
EDR	Environmental Data Record
EIA	Earth Incidence Angle
ESMR	Nimbus-7 Electrically Scanning Microwave Radiometer
FOV	Field Of View
IFOV	Instantaneous Field Of View
LST	Land Surface Temperature [K]
NPOESS	National Polar-orbiting Operational Environmental satellite System
RFI	Radio-Frequency Interference
RMS	Root Mean Square
RMSE	Root Mean Square Error
SDR	Sensor Data Record
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager Sounder
TB	Brightness Temperature
TMI	TRMM Microwave Imager
TOA	Top-of-Atmosphere (i.e., measured by sensor)
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIRS	Visible and Infrared Radiometer System (on TRMM)
VST	Vegetation/Surface Type
VWC	Vegetation Water Content [kg/m2]

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10. Appendix 1: Definitions of the Ice Age Classes

The following definitions are taken from SRD section 3.2.1.1.1.1.

> The following definitions from WMO Sea-Ice Nomenclature and the Handbook for Sea Ice Analysis and Forecasting apply to the EDR table above [Table 3-1 in this ATBD]:
>
> Sea Ice:
> Any form of ice found at sea which has originated from the freezing of sea water.
>
> New Ice
> A general term for recently formed ice which includes frazil ice, grease ice , slush and shuga. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definitive form only while they are afloat.
>
> Young Ice
> Ice in the transition stage between nilas and first-year ice, 10-30 cm in thickness
>
> First Year Ice
> Sea ice of not more than one winter's growth, developing from young ice; thickness 30 cm – 2 m.
>
> Multi-year Ice
> Old ice up to 3 m or more thick which has survived at least two summers' melt.
>
> Old ice
> Sea ice which has survived only one summer's melt; typical thickness up to 3 m and sometimes more.
>
> Supporting definitions:
>
> Anchor Ice:
> Submerged ice attached or anchored to the ocean bottom, irrespective of the nature of its formation.
>
> Frazil Ice:
> Represents the first stage in the freezing process. Fine spicules or plates of ice, suspended in water.
>
> Grease Ice:
> A later stage of freezing than frazil ice when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the sea a matt appearance.

Slush:

Snow which is saturated wan mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

Shuga:

An accumulation of spongy white ice lumps, a few centimeters across; they are formed from grease ice or slush and sometimes from anchor ice rising to the surface.

Nilas:

A thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking 'fingers' (finger rafting). Has a matt surface an is up to 10 cm in thickness. May be subdivided into dark nilas and light nilas.

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